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Potential Environmental Problems of Enhanced Oil and Gas Recovery Techniques

Energy Resources Co., Inc.
Cambridge, MA

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Aug 81

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POTENTIAL ENVIRONMENTAL PROBLEMS OF ENHANCED OIL AND GAS RECOVERY TECHNIQUES

by

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Contract No. 68-03-2648

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16. ABSTRACT

This project provides: (a) an identification of and analysis of available data regarding EOR/EGR related pollutants; (b) an assessment of potential environmental impacts and an identification of possible controls; and (c) recommendations as to research needs. The following processes were studied: steam injection, in situ combustion, CO_2 miscible flooding, micellar/polymer flooding, alkaline flooding, improved waterflooding, advanced hydraulic fracturing, chemical explosive fracturing, and directional drilling.

The existing EOR/EGR environmental impact information (published and unpublished) is critically reviewed during the study and summarized. The effect of EOR/EGR processes on air quality, groundwater quality, water quantity, noise levels, and secondary impacts is the main area of analysis. The nine technological processes are analyzed to determine pollution problems that may occur from their development. An overall impact methodology is used to determine the environmental risks.

This report applies the impact methodology to currently available environmental data collected during the study. A general impact assessment is performed, and the uncertainties that remain about potential environmental effects are enumerated. The report also includes an investigation of control strategy scenarios, proposed data collection and monitoring activities and a section outlining needs for further research on the EOR/EGR environmental concerns.

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PAGE NUMBER

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(4-76)

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report considers the potential pollutants associated with enhanced oil and gas recovery which may impact the environment. The report will be of interest to all those concerned with the potential environmental impacts which may be associated with tertiary oil and gas production.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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(4-76)

PREFACE

The reader should bear in mind that EOR/EGR processes are undergoing continual change as this relatively young engineering technology advances and that the final process and/or processes leading to commercialization may change the recommendations provided by this study.

This pollution assessment addresses itself at one point in time to the nine EOR and EGR processes which are currently being developed. The effect of the potential environmental insult on the media (air, water, and ground) and on the natural resources is examined. Technical, process, and environmental data available to early 1979 were used. This study represents the latest evaluation of these data.

Identified in the Executive Summary are (a) clearly evident environmental problems, (b) pollutant sources of little concern, and (c) environmental issues not resolved due to the current data gaps. As in many industrial activities, their importance will depend on the effectiveness of the operator's planning and execution of methods to avoid or mitigate the various environmental problems associated with the particular recovery technique used at that specific site.

This study is a precursor for later assessments of commercial EOR and EGR technologies, and provides a methodology to assure environmentally sound exploration of new sources of fossil energy. When the final configurations of commercialized EOR and EGR processes become apparent and data gaps have been filled, another environmental study will be in order to consider the advances in the state-of-the-art.

ABSTRACT

This project has developed an analysis of the pollutants attributable to enhanced oil and gas recovery. It has drawn upon new data and old published and unpublished information. The project provides: (a) an identification of and analysis of available data regarding EOR/EGR related pollutants; (b) an assessment of environmental impacts and an identification of possible controls; and (c) recommendations as to research needs. The following processes were studied: steam injection, in situ combustion, CO_2 miscible flooding, micellar/polymer flooding, alkaline flooding, improved waterflooding, advanced hydraulic fracturing, chemical explosive fracturing, and directional drilling.

The existing EOR/EGR environmental impact information (published and unpublished) is critically reviewed during the study and pertinent data are summarized in the final report. The effect of EOR/EGR processes on air quality, groundwater quality, water quantity, noise levels, and secondary impacts is the main area of analysis. The nine technological processes are analyzed to determine pollution problems that may occur from their development. An overall impact methodology is used to determine the environmental risks imposed by the nine processes.

This report applies the impact methodology to currently available environmental data collected during the study. A general impact assessment is performed and the uncertainties that remain about potential environmental effects are enumerated. The report also includes an investigation of control strategy scenarios, proposed data collection and monitoring activities and a section outlining needs for further research on the EOR/EGR environmental concerns.

This report was submitted in fulfillment of Contract No. 68-03-2648 under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 1978 to December 1979 and work was completed as of June 1979. The work upon which this publication is based was performed under Subcontract N8520023SP with the Environmental Monitoring and Services Center of Rockwell International Corporation pursuant to their prime contract with the Environmental Protection Agency.

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3/8"
PAGE NUMBER

EPA-287 (Cin.)
(4-76)

CONTENTS

Foreword . . . iii
Preface . . . iv
Abstract . . . v
Figures . . . vii
Tables . . . x
Acknowledgments. . . . xv

1. Executive Summary . . . 1
   - Introduction . . . 1
   - Trends in the Volumes of Oil & Gas Recovered by Enhanced Technology . . . 6
   - Conclusions . . . 10
   - Recommendations. . . . 17
2. Background. . . . 23
   - Program Objectives . . . 23
   - Project Approach . . . 24
   - Background . . . 26
   - Canadian Enhanced Recovery Activities . . . 44
3. Review of the Literature. . . . 49
   - History and Process Overview . . . 50
   - Projections for Enhanced Oil/Gas Recovery. . . 64
   - Factors Affecting Commercialization Potential 71
   - Environmental Studies of Enhanced Recovery Technologies. . . . 75
4. Identification of Environmental Impacts . . . 87
   - Overview of Environmental Risks due to Enhanced Recovery Pollutants . . . 87
   - Air Quality Degradation . . . 101
   - Noise Generation . . . 116
   - Demand for Water by Enhanced Recovery Processes . . . 123
   - Degradation of Groundwater . . . 144
   - Disposal Processes . . . 195
   - Manufacture of Chemical Flooding Agents . . . 197
5. Pollution Control for EOR/EGR Systems . . . 203
   - Introduction . . . 203
   - Options for Control . . . 203
   - Summary of Available Solutions . . . 205
   - Intermedia Tradeoffs and Technology Options. . 247
6. Needs for Further Study . . . 255
   - Major Uncertainties Regarding Impact . . . 255
   - Proposed Monitoring Activities . . . 258
   - Proposed Highest Priority Research . . . 261

Bibliography . . . 265

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

FIGURES

Number — Page

1 Enhanced recovery technologies considered in the current study 2

2 Pollutant media considered in the current study . . 3

3 Increase in the number of ongoing EOR projects in the United States (1970-1977) 7

4 Potential U.S. crude oil production rate from known fields 11

5 Types of recommendations resulting from present study 18

6 Groundwater laws applicable to water used for EOR and EGR projects 33

7 Steam soak process 51

8 Steam drive process 52

9 Forward in situ combustion process 54

10 Reverse in situ combustion process 55

11 The micellar/polymer flooding process 57

12 Directionally deviated wells stimulated by hydraulic plus explosive fracturing 60

13 Chemical explosive fracturing 61

14 Production, reserves and residual oil-in-place . . . 66

15 Forecasts of tertiary oil recovery 67

16 Potential U.S. crude oil production rate from known fields 70

17 Annual production from unconventional sources of natural gas 76

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

FIGURES (CONT.)

Number Page

18 Location of unconventional gas resources in the analysis of tight gas sands 77

19 Location of unconventional gas resources in the analysis of Devonian shale 78

20 Process/pollutant flow sheet, steam drive 88

21 Process flow sheet, forward in situ combustion . . . 89

22 Process/pollutant flow sheet, polymer, micellar/polymer, alkaline flooding processes 90

23 Process flow sheet, advanced hydraulic fracturing 91

24 Process flow sheet, chemical explosive fracturing 92

25 Process/pollutant flow sheet, directional drilling 93

26 Disposal-well completion methods 99

27 Waste-disposal well 100

28 Air impacts methodology 102

29 Noise impacts methodology 118

30 Oil and gas district boundaries and division of oil and gas offices 130

31 Predicted oil production as a function of fluid injection for the El Dorado field 134

32 Overlay showing relationship of gas shale deposit locations to water availability patterns 137

33 Annual production from unconventional sources of natural gas 138

34 Major routes of groundwater contamination associated with enhanced recovery 145

35 Groundwater impacts methodology 146

36 Transport and fate modeling 181

9-1/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-78)

FIGURES (CONT.)

Number **Page**

37 Case Study: Coaling polymer project, Coalinga field index map 186

38 Generalized process flow scheme for manufacture of polymer showing pollution potential 198

39 Potential physical chemical treatment system 232

40 Potential biological physical chemical treatment system. 233

41 An electrodialysis membrane illustrating the process of NaCl removal from feed saline water. 238

42 Direct and reverse osmosis 240

6-1/2"
9-1/8"
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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLES

Number **Page**

1 Estimates of Enhanced Oil Recovery Potential for the United States 9

2 Estimates of Future EOR Production and 1977 EOR Production 10

3 Enhanced Recovery Projects in the United States, 1978 26

4 Primary and Secondary Air Quality Standards for Seven Criteria Pollutants 29

5 Enhanced Oil Recovery Research 44

6 Canada's Enhanced Recovery Activity. 46

7 Estimates of Enhanced Oil Recovery Potential for the Year 1985 68

8 Summary of Ongoing/Planned EOR Projects - 1976 . . . 69

9 Summary of Current Hurdles to Enhanced Recovery . . 71

10 Predicted EOR Yields Under Two Commercialization Scenarios 73

11 Operating Results of EOR Projects 74

12 Tight gas sands commercialization constraints. . . . 79

13 Devonian shales UGR commercialization constraints. . 80

14 Median Concentration of Trace Metals in Produced Water 95

15 Atmospheric Emissions for Each EOR/EGR Technology 104

16 Summary of Impacts of EOR Air Emissions 105

17 Typical Generator Emission Rate Summary 107

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLES (CONT.)

Number Page

18 Average Emissions of Gaseous Compounds from In Situ Combustions 108

19 Permissible Noise Exposures in the Workplace 119

20 Summary of Noise Levels Identified as Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety 120

21 Summary of Noise Impacts 122

22 Steam Injection Oil Production Data for 1976 (District 3) California 127

23 Steam Injection Data for 1976 128

24 Water Requirements for EGR 136

25 Water Consumption in Coal Conversion and Shale . . . Oil Extraction 140

26 Water Consumption in Coal Conversion and Shale Oil Recovery 141

27 Heat of Combustion of Crude Oils and Multiplicative Factor for Converting Water Consumption (Volume Water per Volume Oil Recovered) to Units of Gallons Water per Million Btu Heating Value of Oil Recovered 142

28 Comparison of Analytical Tasks of the Booz-Allen DOE Study and this EPA Study 147

29 Summary of Levels of Risk Anticipated from Various Activities Carried Out During Enhanced Recovery Programs 151

30 Potential Groundwater Pollutants Associated with Each Enhanced Recovery Process 153

31 Amounts of Chemicals Injected for Typical Projects 155

32 Typical Concentrations of Injection Chemicals . . . 156

33 Tertiary Oil Recovery - Some Typical Microemulsion Compostions 157

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3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLES (CONT.)

Number **Page**

34 Case Study: Coalinga Project, Chemical Volumes Used in Micellar/Polymer Flood 159

35 Case Study: Coalinga Project, Total Volumes of Chemicals Used 159

36 Chemical Volumes for Large-Scale Micellar/Polymer Project 160

37 Case Study: Coalinga Project, Typical Concentrations Used in Micellar Flooding 160

38 Rates of Injection for Three Classes of Chemicals 161 Used by Enhanced Recovery Operations . . . . . .

39 Screening Criteria for Selection of EOR Candidates 163

40 Summary of United States Oil in Place Recoverable by Different Enhanced Methods 164

41 Potential Daily Incremental Production Rate Due to Chemically Enhanced Techniques - Summary for United States 165

42 Rates of Injection for Three Classes for Chemicals Used by Enhanced Recovery Operations 170

43 Concentration of Ions in Connate Waters with Quantities of Oil in Place - Summary for United States 171

44 Typical Connate Water Compositions 172

45 Summary of Acute Toxicity Rating Data 173

46 Ranking Criteria for Table 45 177

47 Acute Chemical Toxicity Rating for Available LD_{50} ORL-Rat Data, EOR Chemicals 178

48 Acute Chemical Toxicity Rating for Available LD_{50} ORL-Mussel Data, EOR Chemicals 178

49 Acute Chemical Toxicity Rating for Available LD_{50} ORL-Rabbit Data, EOR Chemicals 179

50 Acute Toxicity Ranking of Data for EOR Chemicals . . 179

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLES (CONT.)

Number Page

51 Ames Tests on Chemicals Proposed for Use as Cosurfactants 182

52 Ames Tests on Materials Proposed for Use as Mobility Buffers 183

53 Ames Tests on Hydrocarbons Used as Fraction of Micellar Slug 183

54 Ames Tests on Other EOR/EGR Chemicals 184

55 Case Study: Coalinga Polymer Project Temblor Zone II Reservoir Properties and Project Parameters 187

56 Case Study: Coalinga Polymer Project Polymer Concentrations in Produced Waters 188

57 Case Study: Coalinga Polymer Project - Average Values of Polymer Concentrations in Produced Waters 189

58 Case Study: Coalinga Polymer Project - Summary of Injection Tracer Results 190

59 Classes of Materials Used in EGR 195

60 Summary of Control Options 206

61 Ambient Statewide Air Quality Standards 215

62 Proposed Levels of Control for EOR Steam Generators. 215

63 Overview and Summary of Existing Scrubber Systems. . 218

64 Distribution of FGD Systems by Chemical Processes. . 220

65 Summary of Scrubbers Operating on Steam Drives for EOR Applications. 221

66 Major Emerging FGD Processes Investigated in the United States 222

67 SO_x Control Costs. 225

68 Costs of NO_x Removal as a Function of Removal Efficiency, Fuel Type, and Application 227

BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLES (CONT.)

Number Page

69 Efficiency and Costs of Particulate Control Options. 230

70 Approximate Costs of Various Dust Collectors Treating 60,000 cfm of Gases at 68°F 231

71 Particulate Removal Costs for Steam Flood EOR. . . . 234

72 National Petroleum Council Screening Criteria. . . . 248

73 Office of Technology Assessment Screening Criteria . 250

74 Lewin and Associates Screening Critera 251

75 Gulf Universities Research Consortium Screening. . . Criteria. 253

76 Summary of Environmental Tradeoffs 254

ACKNOWLEDGMENTS

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Particular thanks are due to Dr. Walter Unterberg of Rockwell International who supervised all of the work on this project.

SECTION 1

EXECUTIVE SUMMARY

INTRODUCTION

The objective of this study was to identify the areas of environmental concern surrounding the development of enhanced oil and gas recovery[1] and to assess the magnitude of various potential environmental hazards posed by enhanced recovery operations.

This executive summary outlines production trends of enhanced recovery programs, major findings regarding environmental degradation, gaps in control rationales associated with the expansion of enhanced recovery programs, and major recommendations as to what environmental monitoring, pollution control, implementation, and research activities need to be carried out. The body of the report is divided into sections that provide a literature review, develop impacts assessment methods, analyze control technologies, and outline needed research. Within each of the report sections, the nine enhanced recovery technologies are discussed and pollutant inputs to a variety of media are covered. The enhanced recovery technologies and possible pollution effects covered in this report are summarized in Figures 1 and 2.

This study effort was sponsored by the Oil and Hazardous Materials Spills branch of the MERL of the U.S. Environmental Protection Agency. This work was carried out under the direction of Mr. John S. Farlow, Chief, Oil Spills Staff, and under the supervision of Dr. Walter Unterberg, Project Officer, Rockwell International.

---

[1] The term Enhanced Oil Recovery (EOR) in this report refers to secondary or tertiary stages of oil recovery applied to oil fields where the reservoir can no longer be economically produced using natural reservoir pressure (primary recovery). "Enhanced Recovery" involves processes which make use of additional forms of energy, such as chemical or thermal, to achieve further oil production. Enhanced Gas Recovery (EGR) similarly applies to gas bearing sands.

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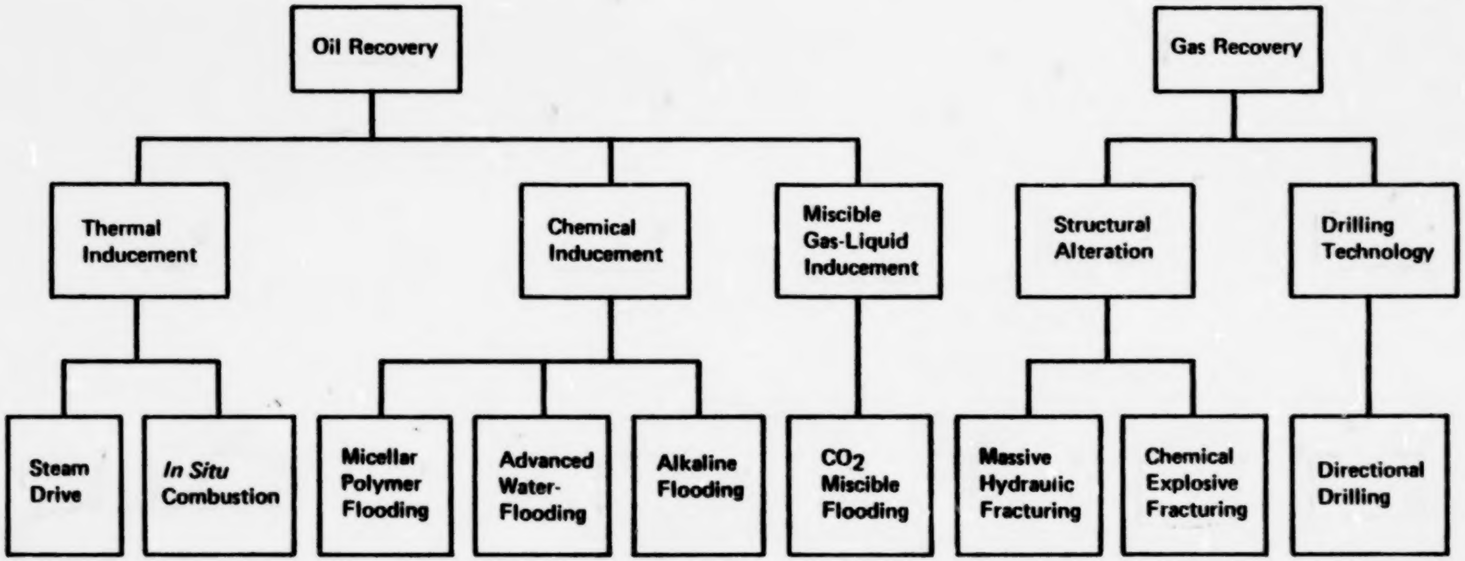
EPA-287 (Cin.)
(4-76)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Gas Recovery
Thermal Inducement
Chemical Inducement
Miscible Gas-Liquid Inducement
Structural Alteration
Drilling Technology
Steam Drive
In Situ Combustion
Micellar Polymer Flooding
Advanced Water-Flooding
Alkaline Flooding
CO_2 Miscible Flooding
Massive Hydraulic Fracturing
Chemical Explosive Fracturing
Directional Drilling

Figure 1. Enhanced recovery technologies considered in the current study.

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EPA-287 (Cin.)
(4-76)

EOR ACTIVITIES							
Construction	Injection Operations	Production Operations	Waste Disposal (Solid & Brine)	Secondary Impacts (Chemical Manufacturing, Refining etc.)			
●	●	●		●	Air	Pollutant Media	Resource(s) or Pollutant Media Affected by EOR Activity
●	●	●		●	Noise		
●	●	●	●	●	Surface Water		
	●	●	●		Ground Water		
●			●		Land Use	Resources	
	●			●	Water Supply		
				●	Demography & Commerce		

Pollutant Media & Affected Resources vs. Related EOR Activity

Figure 2. Pollutant media considered in the current study.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The Oil and Hazardous Materials operating group has the responsibility for developing the means and capabilities of dealing with the spills and discharges of hydrocarbons and other hazardous materials into the environment.[2] At present, the responsibility for studying the environmental issues associated with enhanced recovery also rests with this group. The one previous EPA effort in this general area was an overview study prepared by the Office of Planning and Evaluation (Braxton et al., 1976). More recently, the Office of Policy Planning has carried out studies of environmental constraints on California heavy oil production in general (Bennett et al., 1979a) and on Getty's Kern River generators (Bennett et al., 1979b).

Other work in the area of environmental control of enhanced recovery techniques has been carried out by the U.S. Department of Energy. The DOE has developed environmental readiness documents (U.S. DOE, 1978d,e) and environmental development plans (U.S. DOE, 1978f,g) for their enhanced gas and oil recovery programs, as well as individual environmental impact assessment for DOE-sponsored demonstration projects (O'Banion, 1978a,b,c; Tonnessen, 1977, 1978) and a generic EIS (Mitre Corporation, in preparation, 1979). Study of the air pollution aspects of the problem has been undertaken by the California Department of Oil and Gas (KVB, in preparation) and by several of the oil companies operating large-scale steam generators in Kern and Santa Barbara counties in California (Sheridan, Lynott, and Downie, 1977). The U.S. Department of Energy's Bartlesville, Oklahoma, Research Lab has developed an outline for a comprehensive environmental research program to assist all concerned in the protection of the environment during EOR operations (Donaldson, 1978). The work proposed in DOE's program is designed not only to ensure compliance with environmental regulations, but also to (1) determine the long-term migration of EOR chemicals injected into a petroleum reservoir, (2) determine the rates and products of decomposition of the EOR chemicals in a subsurface environment, (3) determine the migration pattern that can be anticipated for accidental contamination of shallow aquifers and the surface, (4) determine the biodegradation of those compounds that are resistant, (5) determine the feasibility of using cultured microbes to degrade chemicals accidentally contaminating a shallow aquifer, (6) determine chemical means of desorbing and producing chemicals contaminating a shallow aquifer, and (7) examining the toxicity of EOR chemicals. The DOE has also sponsored the development of monitoring guidelines for EOR/EGR operations only in relation to existing or anticipated

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[2] As dictated by Section 40 CFR 151 of the Federal Register.

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EPA-287 (Cin.)
(4-76)

environmental regulations (Booz, Allen, 1978), and a study of the toxicity of EOR chemicals (Silvestro, 1980) is under way.

Nine enhanced recovery technology areas are covered in the current study. Two of these, steam drive and in situ combustion, fall into the general category of thermal enhancement wherein heavy, viscous oil is heated to approximately 300°-400° F, thereby reducing the viscosity and inducing the oil to flow. Four others, micellar polymer flooding, advanced waterflooding, CO_2 miscible flooding, and alkaline flooding, involve the injection of chemical solutions into the reservoir in combination with slugs of water injected under pressure to alter the fluid dynamics of the reservoir and cause oil to be swept by the injected water. Chemical explosive fracturing and massive hydraulic fracturing involve the use of water under pressure or chemical explosion to cause fracture networks in certain types of gas-bearing formations. The fracturing affects formation permeability which is one variable controlling the rate of gas flow out of the formation. The final enhanced recovery technology, directional drilling, involves the oblique placing of well bores to cross natural fracturing zones and increase the surface area in communication with the well to augment gas production.

Each of these nine technologies involves a number of steps during which environmental contamination can occur. The technologies involve implementation of methods tested in laboratory settings using small samples of natural geologic formations or similar material (such as packed sand). This introduces considerable uncertainty as to how fluids injected to enhance recovery may mix with reservoir fluids and travel in the subsurface stratum as a whole. This uncertainty exist mainly because of the known heterogeneity of underground reservoirs and the limited knowledge of reservoir boundaries. Hence, it is difficult to specify where and in what quantities liquids and gases may be emitted or communicated to neighboring formations. Further uncertainty as to the nature and movement of EOR pollutants is caused by the possibility of various reactions between injected fluids and formation pore waters, or chemical degradation products. Because of the sketchy nature of subsurface data[3] in some areas there is the possibility that chemicals may move out of the reservoir into the groundwater environment. Within the context of these uncertainties, this report identifies types of environmental degradation that may occur and makes an analysis of the various categories of pollutant discharges possible with EOR and EGR. A preliminary determination has been made of categories that (1) generally do not appear to exceed environmental regulations, (2) clearly present an environmental problem, and (3) must be further

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[3] This applies globally.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

researched before an assessment can be made. Particular attention was paid in this report to air emissions, surface water discharges, water escaping into the groundwater regime, noise pollution, geological hazards, consumptive water use, secondary impacts associated with increased demands for certain classes of chemicals, and socioeconomic changes.

Analyses of these various types of pollutant emissions and discharges associated with EOR/EGR operations are very important in light of the current global energy situation and DOE's favorable view of EOR/EGR's future role. Millions of dollars are being dedicated to EOR/EGR research and development work and EOR/EGR pilot field projects in order to support the development of commercialization of enhanced technologies aimed at the considerable reserves of hydrocarbons that remain in known reservoirs. Steamflood, steamsoak, in situ combustion, and CO_2 injection projects are already being pursued at a commercial scale. As the push for development of enhanced oil and gas recovery technologies accelerates and prices of competing oil and gas rise, widespread commercialization could occur within five years.

TRENDS IN THE VOLUMES OF OIL AND GAS RECOVERED BY ENHANCED TECHNOLOGY

The number of enhanced recovery projects in the United States has increased from 1970 to 1977 (see Figure 3). More importantly, actual oil recovered has increased from about 150,000 barrels per day in 1970 to about 373,000 barrels per day of enhanced production in 1977 (Noran, 1978). In terms of potential for combined expansion, it has been estimated that the recovery of oil from primary and secondary operations will yield only slightly more than 30 percent of the total oil in place. Primary and secondary oil recovery methods are those that use the natural reservoir state to produce oil (primary) or the addition of water to the reservoir to "push" the oil to producing wells (secondary).

This rate of return leaves 70 percent of the oil remaining in place of which slightly less than half cannot be recovered by EOR. This leaves about 30 percent of the original oil in place as the target for enhanced oil recovery operations. Enhanced oil recovery, which may be carried out in combination with secondary oil recovery in some projects, entails the introduction of energy (chemical or thermal) into a reservoir to force out the oil left in place. The quantity of oil remaining to be discovered, the percentage of this quantity potentially recoverable within various economic parameters, and the potential rate of production are becoming subjects of controversy since various assumptions used in extrapolation

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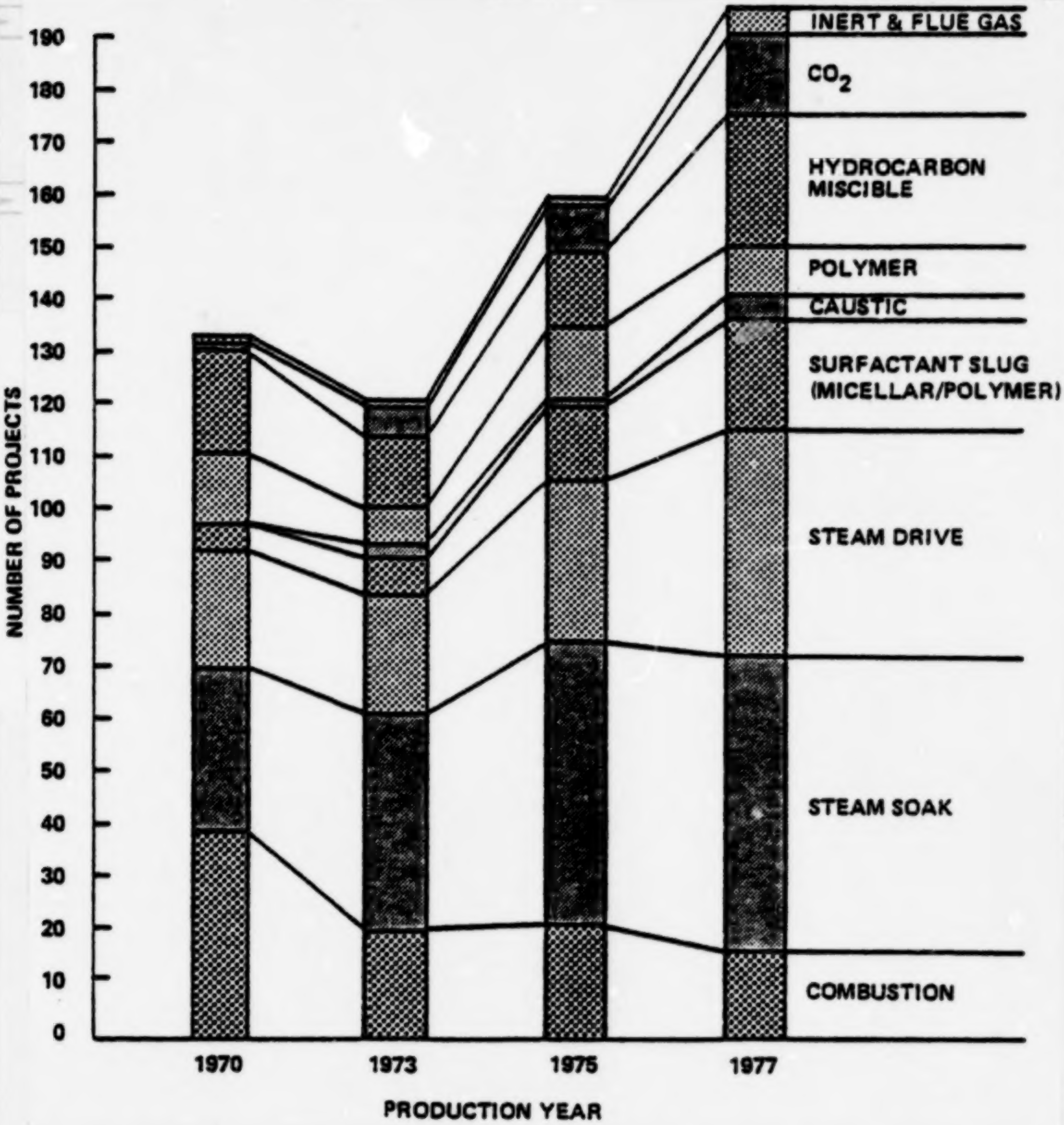

Figure 3. Increase in the number of ongoing EOR projects in the United States (1970–1977). During this period, the number of active field tests overall increased significantly. For chemical flooding processes, surfactant slug projects increased from 5 to 22; polymer projects, after declining from 14 in 1970 to 9 in 1973, grew to 21; caustic field projects increased slightly, from none to 3. Gas projects have been quite successful, with CO_2 flooding projects showing a strong increase and hydrocarbon-miscible projects remaining numerous. Thermal methods outnumbered all others (115 active projects in 1977: 56 steam soak, 43 steam drive, 16 combustion). Steam drive and steam soak have nearly doubled since 1970. Combustion projects, showing the only decline (from 38 to 16), still generate interest; a number of projects were started in 1978, with others planned.

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from available information as well as the proprietary nature of some reserve data lead to different appraisals of oil reserve potential. Some current estimates suggest that proven crude oil reserves in the United States are 29.5 billion barrels as of January 1978 (API, in Schumacher, 1978) and that the undiscovered recoverable reserves may be between 110 and 114 billion barrels (USGS, in Schumacher, 1978).

Whether the remaining oil in place is ultimately tapped will depend on a combination of technical, economic, and environmental constraints. Estimates of potential EOR reserves range from 15 billion barrels to 110 billion barrels. The magnitude of the difference in these estimates of the quantity of remaining oil which can be recovered within given economic and environmental constraints reveals the basic challenge in analyzing the potential for EOR. No consensus exists as to the amount of the additional recovery possible or the time period over which it can or will be recovered (National Petroleum Council, 1976).

Table 1 summarizes the major projections of production by enhanced oil recovery and Figure 4 presents the National Petroleum Council (NPC) view of the overall position of EOR in oil production. In 1976 a survey of enhanced oil recovery operations found that six EOR technologies were already producing 240,000 barrels per day and estimated that EOR production including new steam drive technology should reach 470,000 barrels per day by 1978 or 1979 (OGJ, 1976).[4] The expected contributions of the five EOR techniques to this production and projections of future expansion are shown in Table 2. According to DOE goals, the EOR contribution to total domestic oil production could be 6.5 percent in 1985, the majority of which is expected to be thermally recovered (U.S. DOE, 1978g).

Enhanced recovery technology, if successfully and broadly applied, could significantly increase oil production from United States reserves during the years 1985-2000. Assuming continuation of historical depletion trends, production of current proved reserves (excluding Alaska) will decline to approximately 3 million barrels per day by 1985 and to less than 1 million barrels per day in 1995-2000. Successful application of EOR technology will slow this decline during the period 1985-2000. Oil production from EOR technology may exceed primary and secondary production by the late 1980's (National Petroleum Council [NPC], 1976). Figure 4 outlines potential EOR producing rates superimposed onto the calculated decline curve for production of remaining primary and secondary crude oil from proven reserves in known U.S. fields.

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[4] Level of production actually reached 373,000 barrels in 1977 (Noran, 1978).

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 1. ESTIMATES OF ENHANCED OIL RECOVERY POTENTIAL FOR THE UNITED STATES

Price per barrel of oil assumed for estimate of EOR potential	Potential EOR recovery (billion bbl)	Production in 1985 (million bbl/day)
NPC Study[a]		
$ 5	2.2	0.3
$10	7.2	0.4
$15	13.2	0.9
$20	20.5	1.5
$25	24.0	1.7
GURC[b]		
$10	18-36	1.1
$15	51-76	-
FEA/PIR[c]		
business as usual ($11)	-	1.8
accelerated development ($11)	-	2.3
EPA[d] (1975 $)		
$ 8-12	7	-
$12-16	16	-
FEA/Energy Outlook[e]		
$12	-	0.9
FEA[f] (3 states) (1975 $)		
upper bound $11.28	30.5	2
lower bound $11.28	15.6	1

Note: The reader is referred to the original sources for a detailed description of the scenarios on which the individual studies are based. All of these projections are outdated. With the rapid technological changes and increases in oil prices, new studies of economic and technological potential are critically needed.

[a] National Petroleum Council, 1976.

[b] Gulf Universities Research Consortium, 1973.

[c] Project Independence Report, Federal Energy Administration, November 1974.

[d] The estimated recovery potential of conventional source crude oil, Mathematica, Inc., for U.S. Envivonmental Protection Agency, May 1975.

[e] Energy outlook, Federal Energy Administration.

[f] Review of secondary and tertiary recovery of crude oil, Lewin and Associates, Inc., for FEA, June 1975.

TABLE 2. ESTIMATES OF FUTURE EOR PRODUCTION AND 1977 EOR PRODUCTION[a]

	Daily Production (million barrels ±10%)				
	1977	1985	1990	1995	Percent Contribution[b]
Steam	0.25	0.71	1.32	1.40	45.72
CO_2	0.011	0.15	0.41	0.87	26.71
M/P[c]	0.002	0.04	0.18	0.56	13.98
Special	-	-	-	-	12.73
In situ	0.01	0.01	0.02	0.02	0.86
TOTAL (in M bbl/day)	0.27	0.91	1.93	2.86	100.00

[a] ERDA, 1977, and Noran, 1978.

[b] Percent contribution of each process to total EOR productivity.

[c] M/P = micellar polymer flooding, also commonly referred to as surfactant/polymer flooding or polymer/surfactant flooding.

CONCLUSIONS

This environmental study, which mainly concentrated its efforts on already existing reports and unpublished data (as cited in the bibliography), identified a number of potential environmental problems associated with enhanced oil recovery. Also identified were a number of areas which do not appear to present a problem at this time. One of the final steps in the study was to analyze the present controls being employed as they relate to the potential problem areas outlined by the study. Perhaps of most importance, however, is the finding that further significant research efforts are required before any judgments can be made regarding several important potential areas of enhanced recovery pollution, including: groundwater seepage, health risks of chemicals, chemical supplies and chemical manufacture (secondary impact), and injected chemical degradation products. Some of this research, currently in the formative stages, is being performed by the DOE[5] and others.

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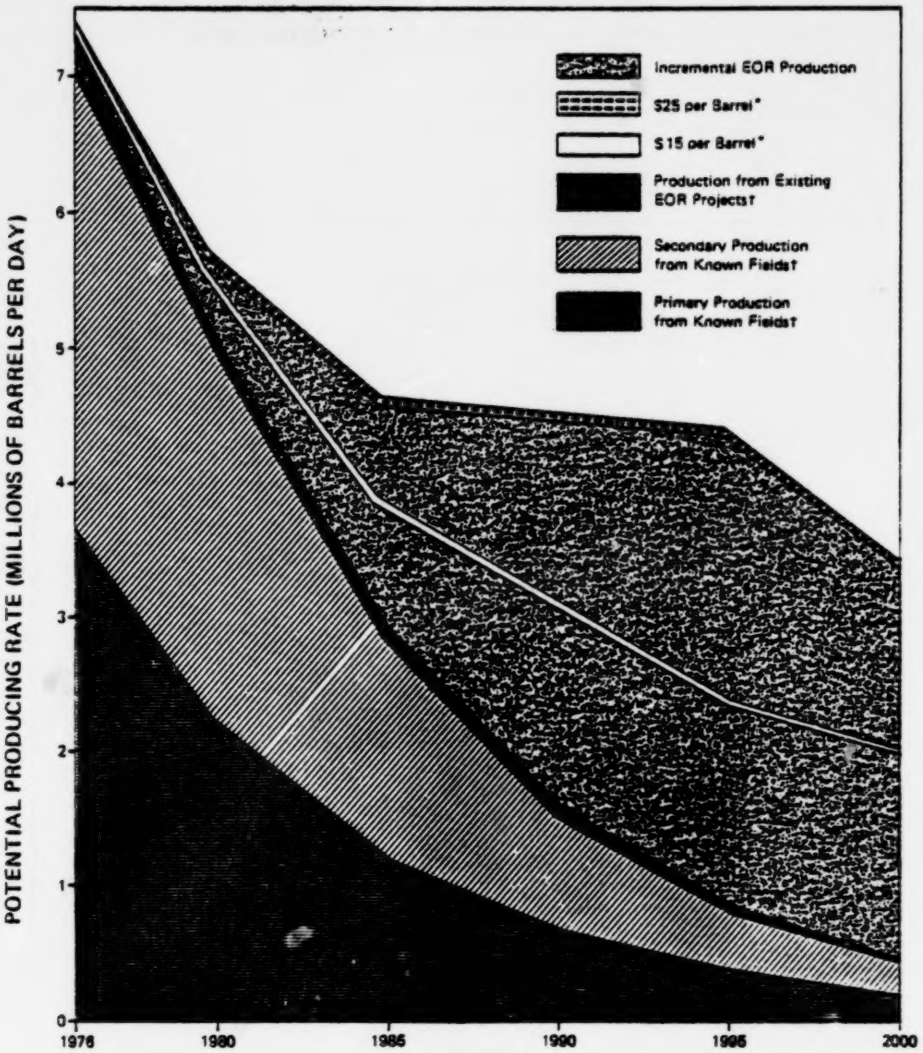
[5] Oklahoma State University, Contract No. EW-78-A-19-001.



*Constant 1976 dollars and minimum DCFROR requirement—10%
† Estimated producing rates based on December 31, 1975 API reserves
Note: Production from the following sources is not considered and will be additive to the rates shown:

- Revisions except as included in API "Indicated Additional Reserves" as of December 31, 1975
- Extensions from realized enlargement of known fields
- New reservoir discoveries in known fields
- New field discoveries after December 31, 1975
- EOR from extensions, new reservoir discoveries, and new field discoveries
- North Slope, Alaska

Figure 4. Potential U.S. crude oil production rate from known fields. (National Petroleum Council, 1976).

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(4-76)

The top three priorities of any further EOR pollution assessment should be: (1) the question of subsurface pollution of water resources, with emphasis on pollutant concentrations and pathways; (2) an evaluation of toxicology of EOR chemicals;[6] and (3) an economic and technological analysis of strategies for steam drive air pollution controls, since thermal technologies are expected to provide over half of future EOR production in the short run. During the course of the data gathering and analysis carried out In this study, it became clear that many of the factors related to enhanced recovery and polluted receiving media are very site-specific. Geologic structure, formation characteristics, aquifer proximity, demography, and water availability are dominant site-specific factors. Hence, the results reported on in this study can only be viewed as analytic tools for specific studies which will need to investigate the environmental risks presented in each state or region and in some cases, individual oil fields or enhanced recovery projects.

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A key factor in the assessment of environmental risks is an understanding of the specific chemicals used in enhanced recovery.[7] Even for those which are generally known, the technologies tend to be in such a developmental state that it is not clear which combinations of chemicals will be employed in the commercialized version of the enhanced technology. Hence, there is a lack of data on and a lack of specific studies of individual chemicals used in enhanced recovery. Thus, it will be necessary to develop a comprehensive baseline data base on the chemical properties and toxicities of the chemicals to be used, when a particular project is reviewed for its environmental acceptability.

Clearly Identified Environmental Problems

The following types of environmental degradation do or may potentially occur as a result of the enhanced recovery activity and need to be studied further in terms of regulatory, monitoring, and research postures by the EPA and DOE:

1. Air emissions from steam generators. Source sampling and dispersion modeling has been performed for steam generators operating under a variety of conditions. In general, SO_x, NO_x, H_2S, and particulate levels are of special concern. This arises from the fact

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[6] A preliminary DOE-funded study dealing with occupational risks has recently been completed (Silvestro and Desmarais, 1980).

[7] Many of the process chemicals are proprietary and in those cases it is difficult to obtain required data.

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EPA-287 (Cin.)
(4-76)

that the oil fields on which thermal recovery is being performed are generally high in sulfur and the most economic way of running steam generators is to burn locally available oil. Burning of this high-sulfur oil results in high SO_x emissions or the economic penalties of employing scrubbers. Also of concern with respect to thermal recovery are the fugitive emissions, from production wells and other sources, of gases generated within the reservoir ensuing from the high temperatures of the thermal recovery operation. This problem is currently subject to study and debate in Kern County, California. The EPA, State of California Air Resource Board, Kern County Air Pollution Control District, DOE, and the major oil companies involved have had major disagreements over necessary levels of air pollution controls and the means which should be followed to impose the controls.

2. Water availability. Most enhanced recovery technologies require the use of significant quantities of fresh water. In many areas this does or most likely in the future will present a problem since enhanced recovery water needs conflict with other water uses. There are a range of options being considered to approach this problem. At the present time several oil companies are performing research on or running pilot projects on the reuse of produced waters, or at least a fraction of the produced waters, in injection processes. Western oil fields suitable for enhanced recovery are situated in areas of net water shortage. Another step being made towards resolution of this problem is the development of EOR chemicals that are compatible with waters with high salt or cation concentrations, thereby decreasing the need for fresh water injection. This developmental work may have another benefit for projects with formations that have freshwater-sensitive clays. If chemicals mixed in formation or saline fluids can be used, enhanced oil recovery would be improved in these cases.

3. Storage of produced brines and produced hazardous solutions. Large quantities of brines and chemically complex produced waters occur as a result of enhanced recovery operations. Current practices vary, but generally involve surface disposal, ocean disposal, reinjection into the producing reservoir, or disposal into another brine formation. These brines are mainly of concern because, although data are generally scanty, there is reason to suspect the presence of metal and other hazardous materials in the brine

simply because of the very large quantities of brine produced. Issues relating to the structural stability of the reservoir following reinjection are also of concern.

4. Disposal of enhanced gas recovery fracturing wastewater. At present, waters used in massive hydraulic fracturing and other fluid-fracturing methods are disposed of in surface holding pits. In some cases these are lined, but many are not. The pits are generally evaporated and the dry residue is plowed over. Of concern are the residues containing potentially hazardous materials which may leach into groundwater supplies.

5. Erosion control. Active enhanced recovery sites involve the continual construction of new pipelines, new wellheads, new injectors, and new roadways. All of these activities can be potentially serious erosion generators. Of particular concern are fields in hilly areas with clayey soils. Where wells can be directionally drilled from good topographic drill sites (hill tops, hill bottoms) to avoid hillside drilling, these problems can be alleviated. Also, well-established erosion control methods developed by the Department of Agriculture can alleviate this problem, which is at present not being dealt with in a large number of reservoirs (including, incidentally, the Naval Petroleum Reserve No. 1, Elk Hills, California).

6. Spill control. The variety of fluids being handled at enhanced recovery sites has a potential for a large number of spill events. The spill prevention guidelines developed by the EPA need to be closely adhered to for all enhanced recovery projects.

7. Surface effluents. Various small-scale surface effluents such as scrubber water, waste oil, cooling water, and produced emulsions often contain hazardous substances and need to be carefully managed in order to avoid surface discharges (spills) that may lead to groundwater contamination or direct discharges into river bodies that then become contaminated.

8. Noise from construction and drilling activity. During the short-term construction and drilling phases of enhanced recovery projects, activities will need to be developed under an integrated plan to maintain acceptable noise levels for workers (an Occupational Safety and Health Association [OSHA] responsibility) and neighboring communities (an EPA concern).

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Current Level of Environmental Controls

With the exception of the Kern River case, little attention has been paid to environmental controls for EOR. This is not surprising and does not represent lack of attention or negligence since most current projects are test or pilot programs. A report such as this clearly is not intended to impose restrictions on experimental projects. Environmental policy has in general exempted experimental programs in various energy fields from strict conformance with environmental regulations. Such exemptions are required to allow the engineering creativity required to develop new energy solutions. Several of the DOE cost-shared projects have involved considerable attention to environmental matters (including the Long Beach and Coalinga projects). In general, the following controls are currently used:

- Controls of emissions from steam-soak generators in California as mandated by the California Air Resources Board (CARB). Current controls include scrubbers for SO_x and vapor traps for hydrocarbons in nonattainment areas. NO_x control strategies are currently under debate.
- Spill control precautions, such as diking, are probably followed at about half of the sites.[8]
- Most produced waters and other liquid wastes are reinjected into the producing formation.
- Erosion controls are followed at about 10 to 20 percent of the sites.[9]
- Attention is paid to workovers and old well cementing prior to almost all projects.
- Drilling muds and EGR liquids are disposed of in unlined evaporation ponds. Evaporites are graded over.
- Water reuse is being tried on a pilot scale.
- Minimal water monitoring is carried out.
- Extensive air monitoring is carried out in California.

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[8] Energy Resources Co. Inc. (ERCO) estimate.

[9] ERCO estimate.

EPA-287 (Cin.)
(4-76)

Pollutant Sources Not of Concern to Enhanced Recovery Operation

A number of the potential recovery pollutant sources that have been developed in several of the generic lists are probably not of a magnitude significant enough to require industry-wide control measures or practices:

1. Noise from routine enhanced recovery operations. The EPA is generally concerned with noise impacts on the general population. Noise generated from injection activities and well production activities in an enhanced recovery operation generally is not of a level to warrant concern to the EPA. OSHA regulates noise exposures encountered by oil and gas workers. Some of these activities may be of concern with respect to industry workers; however, OSHA-type problems are outside the jurisdiction of this report.

2. Air emissions from enhanced recovery technologies other than thermal recovery. A variety of air pollution sources exist in oil operations, including all of the fossil-fuel-driven machinery (trucks, pumps, generators). An analysis of the levels of emissions expected was performed in a previous study (Braxton et al., 1976). At this time it does not appear that these sources are of a magnitude to generate concern.

Environmental Issues not Resolved Due to Data Gaps

A number of critical types of data are not presently available. This precludes drawing any firm conclusions regarding the risk or lack thereof of enhanced recovery operations in the following areas:

1. Groundwater seepage. Further information is required regarding persistence of injected chemicals over time, transport mechanisms out of reservoirs, and movement of these chemicals in freshwater aquifers.

2. Health risks due to chemicals. Most of the chemicals to be employed in enhanced recovery operations do not appear on the various lists of chemicals that have been or are being studied by the EPA. Consequently, toxicological data need to be developed for these chemicals. Preliminary work is currently under way by the DOE (Silvestro, 1980).

3. Secondary impacts associated with chemical supply and chemical manufacturers. Most of the chemical

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

manufacturing processes required to produce the polymers, surfactants, and other chemicals used in enhanced recovery do not fall into the categories which have been studied by the EPA effluent guideline development document series. Further analysis of these industries will be valuable since chemical demands will be high under EOR commercialization scenarios.

4. Degradation products. The range of chemicals into which the injected chemical formulations may degrade in a reservoir have not been studied in an organized fashion. Depending on the nature of the degradation products, the scope of potential enhanced recovery water quality problems may be changed. Preliminary laboratory investigations are under way at the Bartlesville Energy Technology Center.

RECOMMENDATIONS

There are four types of recommendations resulting from this study (Figure 5). First, there is a need for implementation of currently available technology to deal with identified environmental problems. Second, there is a need for research to develop effective control systems using combinations of available technologies. Third, there is a need for development of monitoring programs to provide information regarding patterns of discharges during enhanced recovery projects and conditions of environments in the vicinity of enhanced recovery projects. Fourth, further research is needed on environmental effects in order to resolve the significance of environmental problems for which there are few data.

Implementation of Controls

Control of pollutant discharges should be required for those discharges which have already been demonstrated to constitute a problem and for which control methods exist. However, prior to mandating controls, a cost-benefit analysis of various possible ways of implementing controls is required. At present, this analysis should include current control technologies and the discharges listed below. As further environmental analysis is completed, the cost-benefit analysis should consider all the environmental media. The objective function will need to be specified by the policy making branch of the EPA.

Research already performed and reported on in this study has shown that the following problems are of significance and can be controlled:

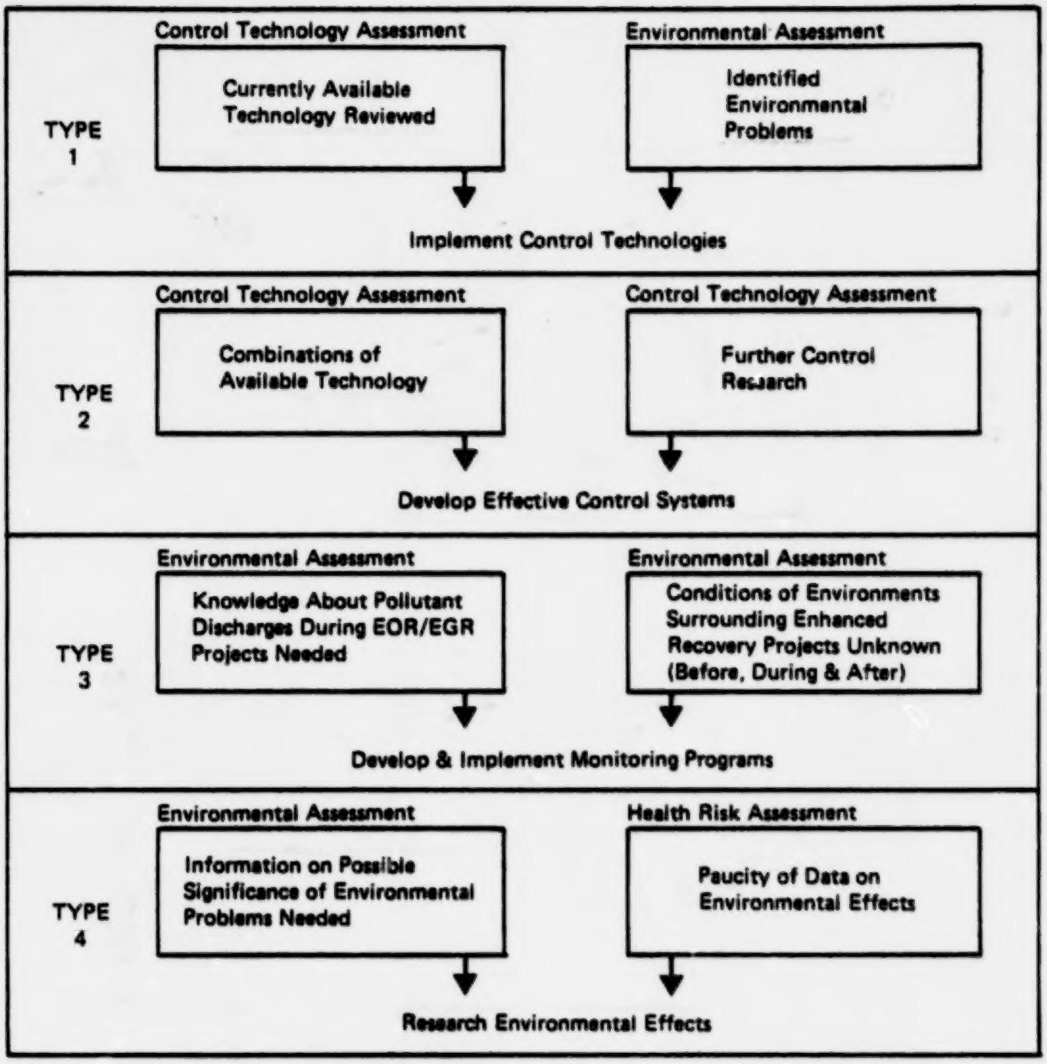
Control Technology Assessment
Currently Available Technology Reviewed
Environmental Assessment
Identified Environmental Problems
TYPE 1
Implement Control Technologies
Control Technology Assessment
Combinations of Available Technology
Control Technology Assessment
Further Control Research
TYPE 2
Develop Effective Control Systems
Environmental Assessment
Knowledge About Pollutant Discharges During EOR/EGR Projects Needed
Environmental Assessment
Conditions of Environments Surrounding Enhanced Recovery Projects Unknown (Before, During & After)
TYPE 3
Develop & Implement Monitoring Programs
Environmental Assessment
Information on Possible Significance of Environmental Problems Needed
Health Risk Assessment
Paucity of Data on Environmental Effects
TYPE 4
Research Environmental Effects

Figure 5. Types of recommendations resulting from present study.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

1. Air emissions from steam drive, SO_x in particular.

2. Some categories of fugitive emissions of H_2S and volatile organics from steam drive and in situ technologies.

3. Surface disposal of hazardous wastes resulting from waters injected into wells for the fracturing of gas shales.

4. Discharging produced waters to a system of limited recycling, producing a reduction in consumptive water use.

5. Control of brines at disposal sites. Since the quantities of brines produced will be large, and many of them contain hazardous substances, it will be important to find suitable receiving media and to keep records of storage areas. Such record keeping is essential until other disposal strategies can be developed.

Control Systems Research

The general needs of research into control systems are: (a) the development of systems of available control to deal with specialized enhanced recovery problems, and (b) the development of comparative analyses of costs of controls versus anticipated benefits. Areas of environmental degradation that are clearly defined and therefore require research at the present time are:

1. Air emissions. Further study of the whole issue of air emissions associated with steam generation is required (pending the outcome of the currently ongoing DOE study on this topic being performed by Radian Corporation). Getty Oil recently temporarily abandoned a fraction of its Kern County, California, steam activities due to SO_x problems. NO_x controls, currently proposed by the CARB, are likely to pose further problems. Emission offset requirements are likely to slow expansion of thermal projects.

2. Produced water. Improved systems would allow the recycling of produced waters as enhanced recovery injection fluids.

3. Nonstructural controls. Options for field management practices and recovery technology methods should be developed as a alternative to technology-based control devices.

EPA-287 (Cin.)
(4-76)

4. Hazardous residues. Current methods, that is, reinjection and disposal in lined pits, merely defer ultimate disposal. Most of the enhanced recovery chemicals can be biologically degraded.[10] Methods for degradation of hazardous wastes (such as composting) for ultimate disposal require development on a commercial scale.

Needs for Environmental Monitoring

Currently, there are few currently existing monitoring programs for tracking possible pollutants produced by enhanced recovery. It would be helpful to develop specific monitoring procedures to check on the efficacy of their pollution abatement efforts. Constituents about which enough is known to warrant such monitoring efforts include:

1. Steam drive air emissions and all fugitive emissions. (Some monitoring is currently occurring in California.)

2. Construction and drilling noises occurring near populated areas.

3. Leachate sampling of enhanced gas recovery holding pits and monitoring of the EGR wastewaters themselves.

4. Monitoring of brine quality to determine heavy metal content. (A data set currently exists at the BETC).

5. Monitoring of produced water qualities for the presence of hazardous organics and trace metals.

6. Monitoring of water quantities used in enhanced gas recovery projects.

7. Monitoring of quantity and quality of scrubber water generated through air pollution controls for steam drive.

Monitoring effort will be useful for establishing the actual presence or absence of potential pollutants identified in the various paper and laboratory studies.

Requirements for Environmental Effects Research

There is a critical need for further environmental research in the following areas:

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[10] Theoretically; practical means for degradation are currently being studied by the DOE and other researchers.

EPA-287 (Cin.)
(4-76)

1. Risk analysis for the determination of expected failure frequency of old well casings in enhanced recovery fields and of geological activity resulting from changes in the structure as a result of enhanced gas recovery fluid dynamic manipulation. Such risk analysis would be applicable to specific projects or types of sites.

2. Baseline data gathering for an analysis of groundwater quality in situations where injected waters leave oil reservoirs.

3. Apply existing analytic and simple simulation subsurface groundwater flow models to allow modeling of environmental impacts from certain types of proposed projects. Such models would be applicable to specific projects or types of sites.

4. Research on chemical degradation and subsurface movement pathways.

5. Toxicological research on classes of chemicals used in enhanced recovery.[11]

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[11] Work on items 4 and 5 is currently under way by the DOE.

SECTION 2

BACKGROUND

The following sections present an analysis of available information regarding the extent of pollutant problems associated with six Enhanced Oil Recovery (EOR) and three Enhanced Gas Recovery (EGR) technologies in the United States. Emphasis is placed on groundwater quality, water quantity, air quality, noise impacts, and on secondary impacts related to chemical manufacture. However, all topics of concern to the National Environmental Policy Act (NEPA) have been considered. The report builds on a number of decision documents prepared by DOE, EPA, and the petroleum industry. A number of recent monitoring studies and research programs have provided data for some analysis of impacts and controls. The analytical results are dependent upon assumptions regarding future EOR and EGR activities, regarding subsurface movement, and regarding the ultimate disposal of brines about which there is no consensus. The report presents recommendations for research, data assembly, and routine monitoring.

This chapter of the report presents the program objectives, reviews current levels of enhanced oil and gas recovery technologies, and the program approach.

PROGRAM OBJECTIVES

This study investigates the types of pollution which may occur as a result of enhanced oil and gas recovery, their impact on the environment, available controls, and recommendations as to further research needs. As a background to this program, a number of paper studies have been prepared by the Department of Energy, the major oil companies, industry organizations, the Office of Technology Assessment, and the EPA. The main focus of these paper studies has been an enumeration of potential pollution problems associated with enhanced recovery activities. The current study has attempted to specifically investigate the various environmental problems mentioned in these reports in order to determine their nature, extent, and relative importance.

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EPA-287 (Cin.)
(4-76)

This study considers the following six tertiary recovery techniques currently being field-tested in major oil-bearing regions of the United States for enhanced oil recovery (EOR):

Thermal processes	
Steam Injection	[1]
In Situ Combustion	[2]
Carbon Dioxide Miscible Flooding	[3]
Chemical Flooding	
Micellar-Polymer Flooding	[4]
Improved Water Flooding	[5]
Alkaline Flooding	[6]

The study also considers the following tertiary gas recovery techniques currently being field-tested in major gas-bearing regions of the United States for enhanced gas recovery (EGR):

Advanced hydraulic fracturing	[7]
Chemical explosive fracturing	[8]
Directional drilling	[9]

The EOR and EGR techniques under consideration involve the transportation, production, processing, and injection of various materials at well sites, with possible resulting impact on the atmospheric, ground and underground environment. The environmental issues of concern include noise levels, air quality, water use, water quality, human health effects, and ecological considerations.

PROJECT APPROACH

This study has attacked a complex series of environmental questions in a 1-year program. It has been restricted to data available in the literature and from agencies and firms actively working in enhanced recovery. The details of the project tasks can be obtained in the study's program plan (Beck et al., 1978). The following is a discussion of issues of scale (present pilot programs versus future commercial scale programs) and procedures of data assembly.

The Scaling Issue

Current enhanced recovery activities, with the exceptions of steam soak, in situ combustion, and CO_2 flooding, exist in the field only with small pilot scale projects. The operating parameters and environmental data which characterize these pilot projects will not always be able to be easily scaled up

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

to commercial scale. Data have been developed based on existing technology. Also, general principles governing how the environmental residuals may change as scaling up to commercial size occurs are discussed. In this study, no attempt has been made to provide specific projections of the parameter changes that such scaling up of technologies may produce. There are too many important data gaps and uncertainties to perform this type of analysis at this time.

Data Assembly

The problem of evaluating impacts of enhanced recovery on the environment is dominated by the need for a variety of data. This study has addressed the data gathering problem with the following approach:

1. The open literature and government research literature were searched from 1970 to the present.
2. Other citations referenced in the documents obtained in (1) above were obtained.
3. A data base characterizing operating parameters of the DOE cost-shared enhanced recovery projects was developed.
4. Additional data for selected DOE cost-shared projects were obtained from DOE and industry personnel.
5. Selected state officials from California, Texas, Oklahoma, and West Virginia supplied information regarding state regulations.
6. Specialists were used to develop certain types of data from the general literature, that is, toxicity/carcinogenicity data and air emission controls.

Data Analysis

In addition to assembly and use of the above data sources, considerable evaluation and analysis of unpublished and published material played an important role in the project. Analytical methodology for the assessment of impacts is developed separately for each pollutant type at the beginning of each of the main divisions of Section Four.

EPA-287 (Cin.)
(4-76)

BACKGROUND

Current Level of EOR Activity: United States

In 1978 approximately 200 enhanced recovery operations were under way, producing an average of 373,000 barrels of oil per day (Noran, 1978). Thirty-seven of these operations are partially funded by the federal government through a cost-sharing program with the Department of Energy at a reported level of $34.6 million. Table 3 outlines the number of U.S. projects, the approximate production, and the government funding for the nine enhanced recovery technologies.

TABLE 3. ENHANCED OIL RECOVERY PROJECTS IN THE UNITED STATES, 1978[a]

EOR Technology	Active U.S. ER Projects (1977)	Approximate (±10%) Production (bbl/day)	Government Funding (MM$)
Thermal			
Combustion	16	10,000	NA[b]
Steam soak	56	250,000	NA
Steam drive	43	VS[c]	12.0
Total	115	260,000	12.0
Chemical			
Surfactant-polymer	22	NA	12.5
Caustic	3	NA	3.5
Polymer	21	NA	NA
Total	46	3,000	16.0
Gas Methods			
Hydrocarbon miscible	15	NA	6.6
Carbon dioxide flood	14	NA	NA
Inert and flue gas	6	NA	NA
Total	35	110,000	6.6
Combined Total	196	373,000	34.6

[a] Noran, 1978.
[b] NA = not available.
[c] VS = very small.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The most productive and currently profitable EOR technology is steam flooding, which accounted for approximately 250,000 barrels of oil, or 67.0 percent of enhanced oil production, and approximately 8.6 percent of total crude oil production in 1978 (Noran, 1978). Carbon dioxide flooding follows with a production of 29.5 percent of oil recovered by enhanced technologies, while in situ combustion and chemical flooding have been estimated to produce 2.6 and 0.8 percent of enhanced oil, respectively.

Steam flooding operations have tended to be a relatively attractive enhanced recovery technology because of low process costs (the inputs, water and energy, have been cheaper than the chemicals required for micellar and micellar-polymer flooding); generally 70 percent or more of the oil is in place because the fields available for steam flooding have not been susceptible to extensive primary or secondary recovery because of the low-gravity nature of the oil; and because the technical issues are straightforward when compared with in situ combustion, chemical flooding, and gas flooding.

However, environmental protection problems are currently slowing the expansion of enhanced recovery operations, particularly the use of steam recovery in Kern and Santa Barbara Counties, California. Conventional steam technology uses high sulfur reservoir oil for the diesel engines and boilers and this results in violations of air emission standards. Additional potential problems which may affect expansion of enhanced recovery technologies generally include water availability, the supply and price of chemicals and the disposal of hazardous materials in an environmentally acceptable manner.

Regulatory Setting

Enhanced recovery projects must comply with numerous environmental laws and regulations, of which the most important and restrictive ones, to be highlighted in this section, pertain to air and water pollution, water use, and accidental oil spills. In each of these areas, and especially air pollution, the relevant legal controls are complex, variable and evolving. Their precise application to any EOR/EGR project can be determined or predicted only after detailed examination of the facts in each case, including the project's location, timing and operating characteristics. The generalizations set forth in the following summaries, then, can do little more than alert the reader to relevant bodies of law, with the understanding that a full-scale legal investigation will have to be undertaken in the course of planning for any particular project.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Air Pollution Control--

Federal and state law in this field is far too complex to be explored here in any detail, but certain features of the law that are most relevant to assessment of EOR/EGR projects will be briefly noted.[12] The use of fossil-fuel burning boilers for steam generation and the emission of fugitive gases from the ground are the principal features of EOR/EGR projects that bring them within the scope of federal and state laws controlling air quality. The 1977 Amendments to the Clean Air Act, P.L. 95-95 (August 7, 1977), codified in 42 U.S.C. 7401-7642, continue the basic framework of federal-state cooperation in improving and maintaining the nation's air quality. The Federal EPA has promulgated national ambient air quality standards (NAAQS) for seven pollutants - sulfur dioxide, particulates, carbon monoxide, ozone, hydrocarbons, nitrogen dioxide and lead[13] - and the states are responsible for formulating and implementing plans (SIPs)[14] that will achieve and maintain those standards. The NAAQS, consisting of primary standards to protect public health and secondary standards to protect public welfare, are expressed as annual mean and short-term maximum concentrations for each of the seven criteria pollutants; see Table 4.

In addition, many states have adopted their own air quality standards (SAAQS), which may be equal to or stricter than the federal, and may cover additional pollutants not yet included in the NAAQS.

Translation of NAAQS and SAAQS into controls on particular polluting sources - a task to be performed by the states in developing their SIPs for all the country's 247 air quality control regions (AQCRs) - has been and continues to be an exceedingly difficult enterprise, which includes assemblage of adequate data and analysis to determine actual air quality, inventories of polluting sources, modeling of dispersion and interaction of pollutants in the atmosphere, and determination of the degrees of abatement and measures of control that are needed to achieve air quality goals.

The states did not have much success in grappling with these requirements under the Clean Air Act of 1970.

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[12] Useful extended discussions of the Clean Air Act, as amended, appear in Environment Reporter Monographs Nos. 26 (5/19/78), 27 (5/4/79), and 28 (5/4/79).

[13] 40 C.F.R. Pt. 50, pursuant to CAA sec. 109.

[14] 40 C.F.R. Pts. 51 and 52, pursuant to CAA sec. 110. In general, EPA's regulations implementing the Clean Air Act appear in 40 C.F.R. Pts. 50-99, which should be consulted for the details of policies summarized in the text.

TABLE 4. PRIMARY AND SECONDARY AIR QUALITY STANDARDS FOR SEVEN CRITERIA POLLUTANTS

Pollutant	Primary Standards	Averaging Time	Secondary Standards
Carbon Monoxide (CO)	10 g/m^3 40 g/m^3	8-hour[a] 1-hour[a]	Same as primary
Hydrocarbons (non-methane) (HC)	160 µg/m^3	8-hour[a] (6 to 9 a.m.)	Same as primary
Lead (Pb)	1.5 µg/m^3	Quarterly Average	Same as primary
Nitrogen dioxide (NO_2)	100 µg/m^3	Annual (arithmetic mean)	Same as primary
Particulate Matter (TSP)	75 µg/m^3 260 µg/m^3	Annual (geometric mean) 24 hour[a]	60 µg/m^3 150 µg/m^3
Ozone (O_3)	235 µg/m^3	1-hour[b]	Same as primary
Sulfur oxides	80 µg/m^3 365 µg/m^3	Annual (arithmetic mean)	1300 µg/m^3

[a] Not to be exceeded more than once per year.

[b] The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 235 µg/m^3 is equal to or less than one.

Consequently, the 1977 Amendments to the Act mandated a second round of planning. By July 1, 1979, states were required to have revised their SIPs for all nonattainment areas, i.e., for areas in which NAAQS had not been fully attained by August 7, 1977. The revised SIPs must tighten abatement requirements so as to assure attainment of NAAQS by 1982 (or by 1987 for ozone and CO under certain conditions). Any state whose SIP revision for controlling pollutants in a nonattainment area was not approved or conditionally approved by July 1, 1979, is prohibited from allowing any major new source of such pollutants to be constructed or modified in that area, until the necessary

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

approval is obtained.[15] In order to be approved, a revised SIP/non-attainment plan must require (*inter alia*) that no major source can be constructed or modified without a permit, which will not be issued unless the permitting agency determines that (1) emissions from the new or modified source will be more than offset by reductions of pollutants from existing sources; (2) that the proposed source will achieve the lowest achievable emission rate (LAER); that all other major sources in the state owned by the same company are in compliance with prescribed emission limitations or abatement schedules; and that the applicable SIP for the nonattainment area is being carried out.[16] The last of these conditions relates to two further prerequisites for approval of SIP/nonattainment plans: that they provide, in general, for implementation of all "reasonably available control measures" as expeditiously as practicable; and that they require, in the interim, reasonable further progress toward NAAQS attainment, including such annual incremental reductions in emissions from existing sources in the area as may be obtained by adopting "reasonably available control technology" (RACT).[17] The Act defines "major stationary source" as any source that directly emits or has the potential to emit one hundred tons per year or more of any air pollutant,[18] after application of air pollution controls.

The foregoing provisions of the CAA may apply to an EOR/EGR facility in a nonattainment area as follows:

(1) If it is an existing facility, the applicable SIP might will require it to abate emissions of SO_2, NO_x, HC and/or TSP, in accordance with a compliance schedule or regulatory deadline.[19] Some combination of technological controls (RACT) and time-phased operating restrictions may be necessary. State and local regulations on these points may vary considerably, in strictness and in substance, from one region to another.

(2) If it is proposed to build a new facility or to modify an existing one, the first question will be whether it is a "major" source. It is not yet clear how this determination will be made when, e.g., the project includes two or more

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[15] CAA sec. 110(a)(2)(I).

[16] CAA sec. 173.

[17] CAA secs. 172(b)(2) and (3); 171(1).

[18] CAA sec. 302(j).

[19] See EPA's proposed amendments to 40 C.F.R. Pts. 51 and 52, 44 FR 51924 (9-5-79), following upon *Alabama Power Co. v. Costle*, No. 78-1006 (D.C. Cir. June 18, 1979) (holding that "potential to emit" must be calculated on assumption that air pollution controls are in place and are functioning as expected).

EPA-287 (Cin.)
(4-76)

steam generators in the same vicinity. Probably, EPA will consider a group of installations constituting an entire plant as "a source" for purposes of determining whether it is a "major" one.[20] So if three proposed new generators at an EOR site would generate a total of more than 100 TPY of SO_2 or NO_x with pollution controls, they will constitute a major source which will be subject to preconstruction review and permit issuance if the state has an approved SIP, and may be prohibited altogether for the time being if the relevant SIP has not yet been approved by EPA.

The CAA also contains important provisions for prevention of significant deterioration (PSD) by new major emitting facilities in clean-air areas. A "major emitting facility" includes (so far as relevant here):

1. Any fossil-fuel boiler or group of boilers constituting a "source"[21] that has a heat input of more than 250 million BTU per hour and that emits, or has the potential to emit, with pollution controls, 100 TPY or more of any air pollutant; and
2. Any fossil-fuel boiler or group of boilers constituting a source that has the potential to emit, with pollution controls, a 250 TPY or more of any air pollutant.[22]

If a proposed new plant fits either of the above descriptions and would be built in an area that already meets NAAQS, the plant will be subject to preconstruction approval and permit issuance by EPA or by a state to which EPA has delegated administration of the PSD program. For this purpose, all areas in the country meeting NAAQS have been designated as Class I, II, or III, and maximum allowable increments in SO_2 and TSP concentrations above August 7, 1977 baseline levels have been respectively assigned to each class.[23] For proposed new fossil-fuel boilers (or other sources), it must be demonstrated that the plant's emissions, together with emissions from other previously approved projects, will not exceed the applicable increment for the affected PSD area. This is a difficult showing to make; it requires extensive monitoring and submission of air quality and other pertinent data. In addition, the applicant must be committed to installing best available control technology (BACT), to undertaking post-construction monitoring, and to going through a public hearing on the proposal.[24]

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[20] Ibid.

[21] Ibid.

[22] CAA sec. 169(1).

[23] CAA secs. 162-164.

[24] CAA sec. 165.

As a rule, a major new plant is subject to PSD requirements if built in a clean area and to nonattainment requirements if built in a dirty area. However, a new plant may be subject to both PSD and nonattainment reviews if:

1. Because of transport and dispersion patterns, emissions from a new plant in a PSD area would affect a nonattainment area, or vice versa.

2. The plant's location is classified as PSD for some pollutants and as nonattainment for others.

Finally, the Act directs EPA to set New Source Performance Standards (NSPS) for individual industrial categories, requiring new plants to use the best system of emission reduction that EPA determines has been adequately demonstrated for each such category.[25] NSPS must be met without regard to whether they are necessary to attain or maintain NAAQS. EPA has promulgated NSPS for particulates, SO_2 and NO_x from fossil-fuel fired steam generators of heat input rate exceeding 250 million Btu per hour.[26]

EPA has delegated administration of NSPS to most states.[27] It is possible, however, that a new plant subject to NSPS, PSD and nonattainment requirements, or to any two of these three, will have to undergo separate preconstruction reviews by the Federal EPA and by the cognizant state agency.

Water Supply[28]--

EOR operations, especially improved chemical, alkaline, micellar-polymer and steam flooding, will require large volumes of water over their lifetimes for injection into oil-bearing strata. This consumptive water use must be considered not only in the context of gross water availability, but also in terms of water allocation to energy technologies under state water law.

Most of the regions in which intensive EOR development is currently taking place are in western states where water resources are also most limited. Such scarcity may pose both physical and legal constraints on use of EOR/EGR technologies. Since water rights are determined, for the most part, by state rather than federal law, a generalization of western water law is presented here as background for the discussion of water-use needs and impacts. Figure 6 summarizes the applicable laws.

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[25] CAA sec. 111.

[26] 40 C.F.R. 60.40-60.46

[27] CAA sec. 111(c)(1).

[28] General source: Gould, 1978.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

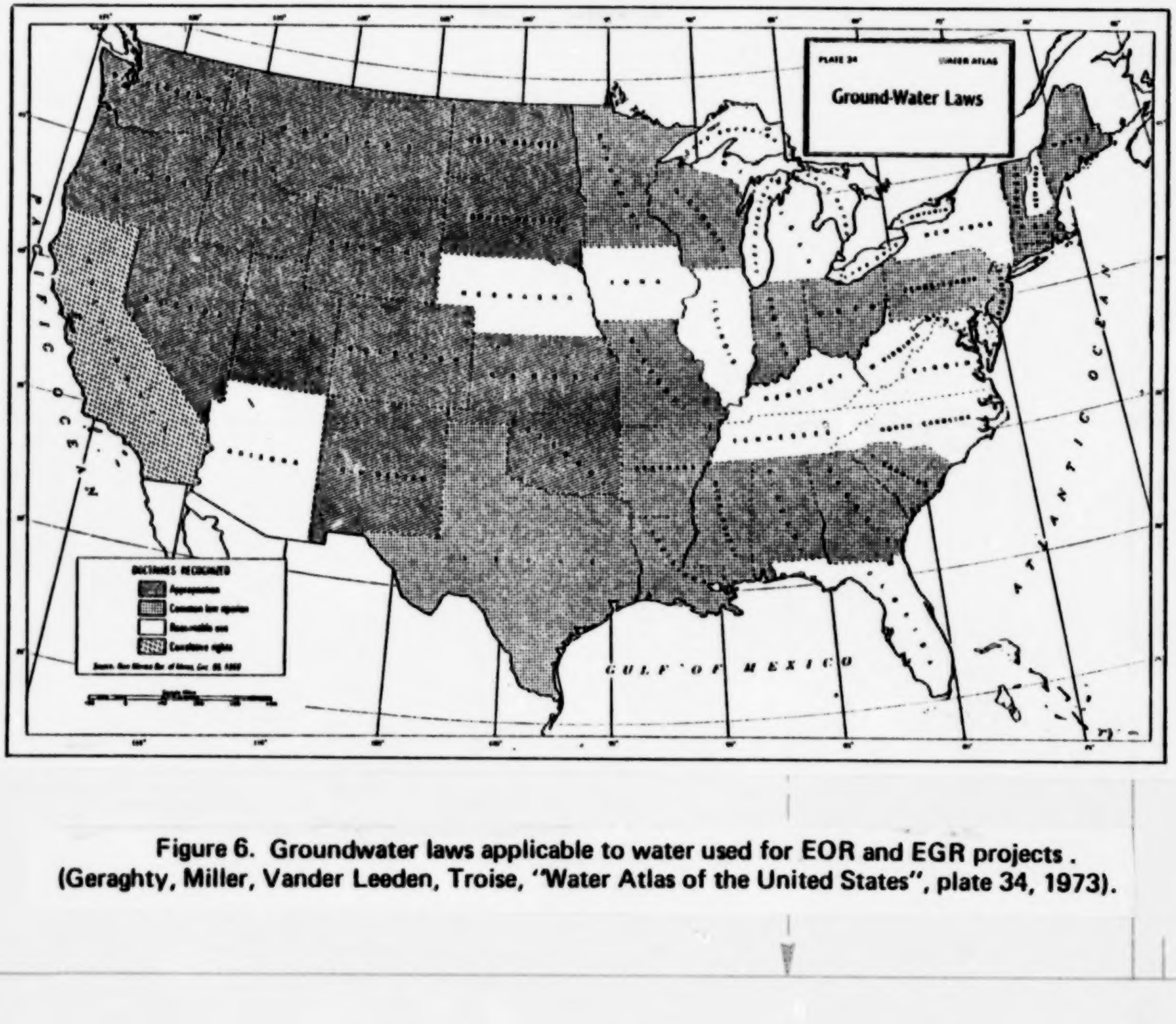
PLATE 34
WATER ATLAS
Ground-Water Laws
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
DOCTRINES RECOGNIZED
Appropriation
Common law absolute
Reasonable use
Correlative rights

Figure 6. Groundwater laws applicable to water used for EOR and EGR projects .
(Geraghty, Miller, Vander Leeden, Troise, "Water Atlas of the United States", plate 34, 1973).

Surface water. Western states generally base surface water allocation and water rights on the traditional doctrine of prior appropriation, under which the first applicant for a permit or first user is the first in right. Two fundamental principles of this doctrine include (1) that "beneficial use" of water (not ownership of riparian land) is the basis of a water right and (2) that the prior water user has the better right, i.e., a superior call upon the water course over all rights subsequently initiated. The effect of the rule of priority for water use is that water shortages fall entirely on those who last gained access to water, rather than being borne by all users.

Groundwater allocation, in most western states, is determined by a permit-appropriation system that is identical or similar to the one used for surface waters. There are notable exceptions, however. Arizona allocates groundwater according to the rule of "reasonable use," which treats each person as the owner of all groundwater under his land and permits him to make any beneficial use of it on the land from which it is withdrawn, or elsewhere if the use does not damage the water supply of other landowners. California, like Arizona, adds to the rule of reasonable use the feature of correlative rights which requires equal sharing in time of shortage. Western states generally accord the same legal status to underground streams as to surface streams, but some states subject percolating waters to the rule of reasonable use. Consequently, the hydrogeology of a particular groundwater source, as well as the system of rights governing its allocation and the pattern of competing groundwater uses, must be assessed in determining whether that source may be available for EOR/EGR projects.

In the administration of water rights, *permits* are required by western states to establish a right to water use. Permits are usually issued and approved by one or more of the following: the State Engineer, a Water Board or Commission, or a Water court. These state administrators enforce the priority system and generally control the use and distribution of water. Proceedings before them may be public hearings or adjudications, in which competing applicants or water users may appear in opposition to the proposed permit.

A permit will be denied or limited as may be necessary to protect senior appropriative rights. In some states, most notably Colorado, a junior appropriator may be allowed to use water currently used by a senior appropriator if injury to the latter will be avoided by an approvable "plan of augmentation." This may involve increasing the supply of water by developing new diversion points, pooling or exchange or water resources, or providing new or substitute supplies. Thus the appropriation doctrine is made somewhat flexible, to the

EPA-287 (Cin.)
(4-76)

benefit of energy developers and others who seek new rights to water in heavily appropriated watersheds.

Transfer of Existing Water Rights to New Uses is a major technique for acquiring such rights. In much of the West, as noted, water supplies are almost fully developed. Therefore, if new uses are to occur in these areas, it will be necessary to transfer water from existing uses. Generally, appropriative rights may be transferred apart from the land on which they are used; accordingly, the corresponding waters can be transferred to a new place for a new purpose if such transfer does not cause injury to other appropriators. Energy companies seeking reliable water supplies often buy long-existing water rights (and the historically benefited properties) in order to be as senior as possible vis-a-vis other appropriators using the same source.

However, standards of beneficial use and of public interest may constrain appropriations and transfers of water rights by energy developers. In general, the use of water for production of energy is recognized as a "beneficial use," but it may be accorded a lower priority than other uses such as water supply for domestic, municipal, livestock and irrigation purposes. These preferences come into play at least when two or more competing applications are received for a source of supply inadequate to serve them all, and may also apply to bump an appropriator for a non-preferred use in favor of a subsequent preferred-use appropriator. Moreover, whether an industrial use can be approved as consistent with the public interest may depend on how the administrator views the effects of such use on fish and wildlife, recreation, agriculture, and any lost alternative uses. The Water Commission of North Dakota, for example, has indicated that it does not wish to allow impairment of the state's water-based agriculture in favor of short-term energy projects. Recent amendments to Montana law prohibit consumption of water for slurry to export coal; will other energy uses that are heavy consumers of water and generators of pollutants suffer a similar fate, even where no export of waters is involved?

Considerations of beneficial use and of public interest introduce additional impediments to the transfer process. If widely and vigorously applied as a preference for environmental over developmental values, these evolving doctrines can make transfer of water to EOR use more difficult in western states.

Public regulation of water allocation is on the increase, and it is no longer determined solely by criteria of economic gain. Transfers of water rights to energy users may be further impeded by state laws requiring impact assessments (especially for large appropriators), consistency with state water plans,

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

maintenance of base or minimum instream flows, withdrawal of specified streams from further appropriation, or reservation of water for future uses. Some of this legislation, along with evolving doctrines of beneficial use and public interest, represents a reaction against energy development for the benefit of other retions. Though energy development may yet come to be recognized as a beneficial and even as a priority use, EOR users and others who propose to transfer water to energy must often be prepared for difficult, expensive, and time-consuming legal process and proceedings before the cognizant state agencies.

The Federal Government's water rights and role in administering water rights may also have to be taken into account by prospective energy developers. If an Act of Congress, authorizing or appropriating money for a federal dam and reservoir, specifies priorities of use for the impounded water, then the administering agency (e.g., Bureau of Reclamation) must see to it that the will of Congress is carried out. In such cases, an applicant for use of federal project water may have to obtain both federal and state permits. The rule announced by the U.S. Supreme Court in *California* v. *United States* (1978) is that the host state may impose, under its own laws, any condition is not inconsistent with any clear Congressional directives respecting the project.

If the applicant himself proposes to build a reservoir or to do other work in navigable waters or tributary wetlands in order to secure the needed water supply, he may also have to obtain both state and federal permits (the latter likely to involve the dredge-and-fill jurisdiction of the Corps of Engineers under sec. 404 of the Clean Water Act). Any federal permit would bring into play the requirement for an Environmental Impact Statement under NEPA, with the probable (and perhaps adversarial) involvement of the Fish and Wildlife Service and other conservationist agencies concerned with maintenance of ecosystems and instream flows.

The Federal Goverment may assert senior water rights of its own, which could effectively cast into doubt the availability of hitherto unappropriated surface or groundwaters for energy development. It is well established that a federal reservation of lands in the arid West implies a simultaneous reservation of water sufficient to utilize those lands for the purposes for which they were reserved (e.g., wildlife preserves, national parks, military bases). The dates and quantities of such reserved rights have not been fully determined - a risk-factor of uncertain dimensions that must nonetheless be considered wherever federal interests may be affected by a proposed new water use.

TYPING GUIDE SHEET
EPA-287 (Cin.)
(4-76)

Indian water rights are a significant phase of the reserved rights doctrine. Under early treaties with the United States, Indian tribes may enjoy reserved water rights superior to and independent of appropriative rights sanctioned by state water law. This situation presents both constraints and opportunities. Energy developers may negotiate with Indian tribes for access to their water rights, without having to apply for appropriation permits under the laws of any state. As quasi-sovereign entities, the tribes can lease their waters to whomever and for whatever purposes they will. Lately, however, the Bureau of Indian Affairs has been backing the tribes in their insistence on negotiating and renegotiating for terms more favorable to themselves as lessors of water rights to industries for uses off the reservations.

Groundwater Quality Control--

Injection of chemicals for EOR/EGR production, reinjection of brines, and maintenance of waste-disposal lagoons are features of enhanced recovery technologies that must be assessed in the light of federal and state groundwater law.

State laws continue to govern protection of groundwater quality, guided to some degree by federal law. Thus, under the Federal Clean Water Act, P.L. 92-500, 33 U.S.C. 466 et seq.:

- A state may approve injection of water and other material into a well to facilitate production of oil or gas, and may also approve well-disposal of water derived from that production, if the state determines that such injection or disposal will not result in degradation of ground or surface waters (sec. 502(6)).
- State programs for administering the National Pollutant Discharge Elimination System (NPDES) must include adequate authority to control the disposal of pollutants into wells (sec. 402 (b)(1)(D)).
- State plans for areawide wastewater management must include processes to control disposal of all pollutants that could adversely affect groundwater quality (sec. 208(b)(2)(J) and (K)).

Quite apart from federal law, the states have traditionally exercised predominant authority over groundwaters and related land use. Protection of drinking water supplies is enforced under state health codes, which may prohibit disposal wells or lagoons in the vicinity of water wells. Some states prohibit deep-well injection altogether. For purposes of water quality regulation, "waters of the state" are frequently defined as including underground waters, and there is a trend among the states towards establishing groundwater quality

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PAGE NUMBER
EPA-287 (Cin.)
(4-75)

standards, paralleling those which exist everywhere for surface waters. Increasingly, states are also regulating the storage and disposal of hazardous wastes, primarily with a view to protecting groundwater resources. Texas, for example, has regulations prohibiting location of surface impoundments in aquifer recharge areas or at other sites hydraulically connected to groundwaters. Through zoning and siting laws, a number of states impose strict land-use controls on activities in critical recharge zones. Such controls may also be prescribed by land-management plans or by aquifer protection ordinances for environmentally sensitive areas. EOR/EGR developers should therefore look with care at the relevant bodies of state (and) local laws pertaining to water supply, water quality, land use and waste management.

The Federal Safe Drinking Water Act (SDWA) requires EPA to publish and periodically update a list of states that are in need of underground injection control (UIC) programs for protection of drinking water sources, and to establish minimum requirements for those programs. UIC programs must prevent injection that endangers present or potential drinking water sources via migration of pollutants through the ground. EPA has proposed to define such sources as including all aquifers or portions thereof containing fewer than 10,000 parts per million of total dissolved solids (44 FR 23738, April 20, 1979) - a definition broad enough to include most of the nation's groundwaters.

However, the Act specifies that UIC requirements must not interfere with or impede (1) the underground injection of brine or other fluids brought to the surface in oil or natural gas production, nor (2) any underground injection for secondary or tertiary recovery of oil or natural gas, "unless such requirements are essential to assure that underground sources of drinking water will be not be endangered by such injection" (sec. 1422(c)). The "unless" clause literally undercuts the non-interference provision, but the intent of Congress here is no doubt to strike a balance between measures necessary for protection of water supplies and burdens to be imposed on oil and gas developers.

According to EPA's proposed regulations (q.v.), permits will be required for both existing and new Class II wells - which include all injection wells associated with oil and gas production. New wells are to have casing and cementing adequate to protect aquifers from migration of fluids; wells in an existing injection field need meet only the standards historically applicable to that field. Mechanical integrity would also have to be demonstrated, initially and at 5-year intervals. Applicants for new Class II permits would be required to assess nearby wells and to correct those which were improperly completed or plugged. Limitations on pressure and rate of injection would apply to Class II wells, whose operators would have to monitor pressure and volume of injection and quality of injection fluids, and submit annual reports to the control authority. These and other proposed requirements may be modified by EPA's final UIC regulations, which are expected to appear in the spring of 1980.

The SDWA requires EPA to promulgate and enforce UIC programs in listed states that choose not to participate or that fail to develop and operate approvable programs of their own. A similar structure of federal-state relations is created under Subtitle C of the Resource Conservation and Recovery Act (RCRA), which regulates on-land disposal of hazardous wastes and may therefore apply to disposal lagoons incident to EOR/EGR operations. Standards and permit systems for treatment, storage and disposal of hazardous wastes are expected to be promulgated shortly by EPA under RCRA secs. 3004 and 3005. Protection of groundwaters from on-land disposal of industrial wastes will be a major objective of these regulations. Waste lagoons may have to be designed or retrofitted so as to prevent discharge of hazardous pollutants to groundwaters.

It is expected that the surface impoundment assessments currently in progress under SDWA sec. 1442(a)(8)(c) will yield data of use to EPA in formulating or revising its standards for ground-water protection under RCRA Subtitle C. EOR/EGR companies must stay alert to expected regulatory developments under both Acts.

Spill Prevention Control and Countermeasure Plans--

Owners and operators of facilities that handle and store oil or hazardous substances may be required to develop and implement plans for the prevention and containment of accidental and chronic discharges from such facilities. These plans - called "spill prevention control and containment" plans (SPCCs) - are required under the authority of Sections 304(e) and 311(j)(1)(C) of the Federal Clean Water Act. 33 U.S.C. Secs. 1314(e), 1321(j)(1)(C). Administration of SPCC requirements is divided between the EPA, the Coast Guard and the Department of Transportation. EPA has jurisdiction over onshore and offshore non-transportation related facilities. DOT and Coast Guard have authority over transportation related facilities.

Some SPCC regulations have been published:

- 33 C.F.R. Part 154. Coast Guard regulations relating to vessels and vessel transfer facilities.

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PAGE NUMBER

EPA-287 (Cin.)
(4-76)

- 40 C.F.R. Part 112. EPA oil spill SPCC regulations for non-transportation related facilities. These regulations apply to all types of facilities, irrespective of whether they are subject to NPDES permits.

Other regulations have yet to be adopted:

- On September 1, 1978, the EPA proposed hazardous-substances SPCC regulations for non-transportation facilities (proposed 40 CFR Part 151). 43 Fed. Reg. 39275-80. These regulations would apply only to facilities that are the subject of NPDES permits, and would become applicable to such facilities at the time the permits were renewed.

- The EPA is contemplating further hazardous-substances SPCC regulations, to apply to facilities that do not have NPDES permits.

- The Department of Transportation has authority to issue SPCC regulations governing other types of transportation activities (e.g., pipelines, railroads and trucks), but has not yet done so.

Other Issues Not Specifically Covered by the Current Regulatory Structure

Issues of concern in evaluating enhanced recovery technologies include the following:

1. The possible contamination of groundwater by chemicals for which toxicity and carcinogenicity testing have not been done and, therefore, for which "safe" levels have not been determined. Contamination routes include:
   - Injection for recovery and leakage through faulty well-casings.
   - Spillage in transport, mixing, or injection.
   - Reinjection for underground disposal.
2. Unregulated or uncontrolled air emissions that may cause detrimental health or environmental impacts. These may include:
   - Fugitive emissions of hydrocarbon fractions from thermal operations.
   - Possible emission of vaporized trace metals from in situ combustion operations.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

- Contribution to possible global effects of raising ambient CO_2 levels.
- Currently occurring emission of fine particulates from the burning of crude oil that may contribute significantly more to health risks than the currently controlled coarser particulates.

3. Types of chemical manufacture not covered by the effluent guidelines (U.S. EPA, 1974; U.S. EPA, 1975). For example, polymer effluent as specified in the following two guidelines does not apply to most of the specific polymers used in EOR. Thus, the effluent from manufacture of these chemicals is potentially uncontrolled.

Current Environmental Assessment Practices

Under the National Environmental Protection Act (§6.510 amended by FR 49793, October 1978), "an adequate environmental assessment must be an integral, though identifiable, part of any facilities plan submitted to the EPA." The information in the facilities plan, particularly in the environmental assessment, will provide the substance of an EIS if it is required.

Environmental Assessment--

Analyses constituting an adequate Environmental Assessment include the following:

1. Description of the existing environment (with documentation)
2. Evaluation of alternatives.
3. Environmental impacts of the proposed action.
4. Steps to minimize adverse affects.

Environmental assessments have been prepared by the DOE for the technology-demonstration projects which are government-industry cost shared. These reviews of potential environmental problems provide general guidelines regarding possible problem areas.

Environmental Impact Statement--

An Environmental Impact Statement is necessary for a project when the following (of several) criteria apply:

1. "The action may directly or through induced development have a significant adverse effect upon local ambient air quality, local ambient noise levels,

surface or groundwater quality, and fish, wildlife, or their natural habitats" (§6.608[5]).

2. "The project consists of field tests involving the introduction of significant quantities of hazardous substances into the environment" (§6.608[5]).

The cognizant agency renders judgments regarding the need for an EIS subject to the ultimate approval of the Council on Environmental Quality. It is the regional EPA administrator's responsibility to determine the scope of the EIS. The administrator should determine if an EIS should be prepared for a specific project or technology area, and which environmental areas should be discussed in greatest detail (§6.512[6][f]).

Current Monitoring Practices

Environmental monitoring of enhanced recovery impacts is necessary for measuring air emission levels, groundwater quality with respect to injected ER chemicals, and noise levels.

Air Emission Levels--

Extensive monitoring of ambient levels of SO_x, NO_x, and particulates is being undertaken in Kern and Santa Barbara Counties, California, by oil company and California Air Quality Control Board contractors, and levels of CO, hydrocarbon, and H_2S associated with steam soak and drive are also being studied (KVB, 1979). Data on emissions from steam generators are sufficient to allow modeling for predicting environmental impacts and for considering control options (SAI, 1978).

Noise Level Monitoring--

Although noise level monitoring for ambient noise levels has not been done for oil recovery operations it is not expected to be a big problem. Data on the noise levels of specific equipment sources are available and suggest that the only problems will be that certain kinds of equipment may exceed EPA guidelines during drilling and some ER activities; in particular, nighttime guidelines are exceeded by the 24-hour drilling activities.

Current Control Precautions

A variety of controls are currently employed to reduce air emissions, to regulate well safety and to preserve groundwater quality.

Air Emission Controls--

The boilers used in steam flood operations are a major source of ER-related air emissions. Controls for SO_x, NO_x, particulates, and hydrocarbons from these boilers are now being implemented in California, where the California Air Resources Board (CARB) has denied permission for further expansion of steam flooding without protection of ambient air quality. Current control options include: scrubbers, importation of low-sulfur oil, burning natural gas with low H_2S, and fluidized-bed pyrolysis using petroleum coke.

Groundwater Quality Regulations--

The Safe Drinking Water Act (1974 as amended in 1977) requires that "applicants for injection permits must satisfy the State that the underground injection will not endanger drinking water sources" (§1422[b]). Individual states have therefore developed regulations for the drilling, setting, maintaining, and sealing of wells, designed to minimize the possibility that chemicals or oil will leak through the well and casing into adjacent aquifers. Likewise, state injection permits that require controls for reinjection of produced water or waste into the same, or other, permeable strata must be approved. The injection strata must be shown to be contained by surrounding impermeable strata and considered geologically sound so that injected materials will not leak out. Other state-regulated measures to protect groundwater quality include: spill control (barriers, transport and handling precautions), erosion controls, and impermeable linings for the holding ponds used in the evaporation of water from fluids produced in EGR operations.

Water Requirements

The fresh water requirements for EOR steam flooding and chemical flooding operations are large, ranging between 7.23[29] and 0.52[30] barrels of water injected per barrel of oil produced, and as much as 50 million barrels annually for a full-scale steam flood operation. Chemical flood water requirements can range between 3.8[31] and 38.0[32] barrels of water injected per barrel produced oil. For western states like California, Texas, and Oklahoma, where fresh water supplies can be limited at certain times of the year, EOR operations may be affected or impeded by regional water use priorities.

The wide range of water use to oil recovered is a real statistic and not a data problem. Depending on the reservoir geology and hydrology and on the production history of the reservoir, conditions will vary. A further complication is the change in ratio, usually increasing over the life of an enhanced recovery project.

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[29] Railroad Gap, Amnicola Field.

[30] Poso Creek, Etchegoin-Chanae Field.

[31] El Dorado Field; micellar-polymer; average over the life of the project.

[32] N. Burbank Field; micellar-polymer; average over the life of the project.

Some technological changes currently being tested may allow brines and treated sewage to be substituted for fresh water in some phases of the flood, and this has been demonstrated for an alkaline flood project (Wheeler, 1979). The resulting reduction of demand for water with competing uses could be a necessary move for EOR as demand for water resources increases.

CANADIAN ENHANCED RECOVERY ACTIVITIES

Enhanced recovery is also a technology being developed in Canada. The major Canadian projects have been included here for comparison with the U.S. efforts. The major tar sands programs organized by the Canadian government have been subjected to considerable environmental scrutiny.

Much of the oil found in Canada is heavy oil, in the tar sands of the Alberta and Saskatchewan provinces. The major Canadian enhanced oil recovery work has been in the development of methods to extract oil from these tar sands. This has involved considerable laboratory testing and some pilot field projects. Table 5 indicates the major Canadian research centers involved in EOR development. Since 1970, Canada has focused on the development of thermal recovery methods for the extensive heavy oil and tar sand deposits of the oil producing provinces. The introduction of large-scale thermal operations is being planned and there are a number of environmental

TABLE 5. ENHANCED OIL RECOVERY RESEARCH[a]

Institution	Process	Type of Resource
Alberta Research	Steam drive	Tar sands
Petroleum Recovery Institute	Huff and Puff Steam drive	Heavy oils
University of Calgary	In situ combustion	Tar sands

[a] There have also been several projects in Alberta and Saskatchewan using alkali floods, micellar-polymer floods, and improved water floods. The main focus, however, has been on thermal methods.

questions being raised. The remaining enhanced oil recovery processes have not been developed extensively in Canada and there has been no significant environmental concern about them.

Current Canadian EOR Activity

Ongoing Projects - Private Sector--

Ongoing EOR projects in Canada (Noran, 1978) are listed in Table 6. As of January 1978 these included: 15 steam (drive and soak), 9 CO_2 floods, 11 in situ combustion, and 4 polymer flood projects; most of these are on a small pilot scale.

Several of the privately owned projects in Alberta are presently being expanded to commercial scale. In 1975 an in situ combustion, heavy oil recovery pilot project was begun by the Imperial Oil Company near Cold Lake, Alberta. This project is now planned to involve the drilling of 10,000 wells and the production of 140,000 barrels of oil per day. Two other large-scale projects are now in progress in the Saskatchewan-Alberta border fields: an in-situ combustion project at Gregoria Lake (Athabasca), operated by Amoco Canada and Aostra; and a cyclic steam project at Peace River, operated by Shell Oil Company, Ltd. These projects have been the subject of Alberta government environmental hearings and study. Environmental concerns resulted in considerable redesign in and delay of the Cold Lake program, mainly regarding wastewater disposal and airborne sulfur emissions.

Government/Industry Cost-Sharing Projects--

In the last 4 or 5 years the Canadian federal and provincial governments have cooperatively become directly involved in support of three enhanced oil recovery projects. As financial support from both levels of government for EOR projects is a result of the Canada-Saskatchewan Heavy Oil Agreement. The oil company involved in each case is responsible for one-half of the project costs; the Canadian government and the Saskatchewan government have each agreed to fund one-quarter of the costs for each project. Current projects are:

1. Texas Gulf, Inc. is operating the Meota Steam Project on behalf of two Canadian companies. The project is being converted from a cyclic steam process to that of steam drive. It involves nine wells, the center one of which will be converted to continuous steam injection.

2. The Murphy Oil Company will apply a combined combustion and steam flooding technique to heavy oil at its Eyehill Project. Twenty-five new wells will be drilled and nine of them will be used for air

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TABLE 6. CANADA'S ENHANCED-RECOVERY ACTIVITY[a]

Type of Project[b]	Deposit/ Field	Pro- vince	Operator	Start Date	Area Acres	Number Wells		Pay Zone	Forma- tion Type	Poros- ity (%)
						Prod.	Inj.			
SD	Athabasca	Alta.	Texaco	1976	3.75	6	7	McMurray	Uncon.	34
SD	Athabasca	Alta.	Texaco	6/72	10	12	5	McMurray	Uncon.	34
SS	Bodo	Alta.	Tesoro	11/75	-	3	-	60 ft	SS	34
SS/Comb.	Buffalo Creek	Alta.	Union	1977	-	4	1	Grossmount	Carbo- nate	-
SS	Cold Lake	Alta.	Union Texas/ Great Northern	9/75	-	15	-	1,300 ft	-	-
SS	Cold Lake	Alta.	Imperial	197	-	-	-	-	-	-
SD	Cold Lake	Alta.	Norcen/JOSC	1977	-	12		-	-	-
SS	Cold Lake	Alta.	Gulf Oil Canada	1977	-	12		-	-	-
SS	Cold Lake/ Ft. Kent	Alta.	WECO	10/75	45	6	-	-	-	-
	Cold Lake/ Ft. Kent	Alta.	BP/Aostra		-	-	-	-	-	-
SS	Cold Lake/ Lindberg	Alta.	Murphy	8/74	140	6	1	Lower Grand Rapids	SS	33
SS	Hazeldine	Alta.	Murphy	9/75	10	1	-	Mannville	SS	33
SS & SD	Lloydminister/ N. Blackfoot	Alta.	Husky	11/77	10	2	1	-	Uncon.	34
SD	Peace River	Alta.	Shell/Aostra	1979	50	24	7	90 ft	SS	28
SS	Meota	Sask.	Saskoil, Texas Gulf Inc Total Petroleum		-	5		-	-	-
Comb.	S. Cold Lake/ Kitscoty	Alta.	General Crude Oil		960	95		-	-	-
Comb.	S. Cold Lake/ Silverdale	Alta.	General Crude Oil		640	52		-	-	-
F. Comb.	Aberfeldy	Sask.	Husky	7/69	760	30	5	Sparky	SS	35
F. Comb.	Battrum #1	Sask.	Mobil	10/66	2,900	73	9	Battrum-Roseray	SS	

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TABLE 6. (CONT.)

Type of Project[b]	Deposit/ Field	Pro- vince	Operator	Start Date	Area Acres	Number Wells		Pay Zone	Forma- tion Type	Poros- ity (%)
						Prod.	Inj.			
Comb.	S. Cold Lake/ Silverdale	Alta.	General Crude Oil		640	52		-	-	-
F. Comb.	Aberfeldy	Sask.	Husky	7/69	760	30	5	Sparky	SS	35
F. Comb.	Battrum #1	Sask.	Mobil	10/66	2,900	73	9	Battrum-Roseray	SS	26
F. Comb.	Battrum #2	Sask.	Mobil	11/65	800	13	2	Battrum-Roseray	SS	27
F. Comb.	Battrum #3	Sask.	Mobil	8/67	2,000	18	3	Battrum	SS	25
F. Comb.	Golden Lake	Sask.	Husky	7/69	140	12	3	Sparky	SS	35
Cofcaw	Athabasca	Alta.	Amoco	9/71	10	10	-	McMurray	Uncon.	35
Cofcaw	Athabasca	Alta.	Amoco/ Aostra	1976	23	16	9	McMurray	Uncon.	35
Cofcaw	Bodo	Alta.	Tesoro	8/75	20	4	1	61 ft.	SS	34
Cofcaw	Silverdale	Sask.	Murphy	8/73	40	7	1	Sparky	SS	34
Hydro. misc.	Ante Creek	Alta.	Amoco	5/68	6,400	14	6	BHL	Dolo.	-
Hydro. misc	Golden Spike	Alta.	Imperial	1964	1,280	46	5	489 ft.	LS	9
Hydro. misc.	Pembina	Alta.	Texaco	1/72	5,540	29	4	Cardium	Congl.	9
Hydro. misc.	Rainbow AA	Alta.	Mobil	9/72	690	4	2	Keg River	LS	1
Hydro. misc.	Rainbow T, Z, FF	Alta.	Imperial	6/69	511	4	2	Keg River	Dolo.	7
Hydro. misc.	Rainbow S.B.	Alta.	Amoco	1972	640	3	1	Keg River	LS	5
Hydro. misc.	S. Swan Hills	Alta.	Amoco	7/73	16,000	98	22	Beaverhill Lake	LS	8
Hydro. misc.	Wizard Lake	Alta.	Texaco	11/69	4,800	16	12	Leduc	Dolo.	10
Hydro. misc.	Willmar	Sask.	Gulf	5/77	-	4	1	-	-	-
Polymer	Jenner	Alta.	Ashland	1969	2,500	16	3	Manville	SS	29
Polymer	Pembina	Alta.	Mobil	11/71	320	12	6	30 ft	SS	10
Polymer	Taper Mannville D Unit #1	Alta.	Chevron	1/71	560	12	2	Manville	SS	23
Polymer	Taber South	Alta.	Ashland	1967	1,200	27	4	Manville	SS	26

[a] Noran, 1978.

[b] SS = steam soak; SD = steam drive; Cofcaw = combination of forward combustion; Hydro. misc. = Hydrocarbon miscible.

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EPA-287 (Cin.)
(4-76)

injection to support combustion. The project funding includes money for conducting environmental assessment.

3. Mobil Oil Canada Ltd. will be operating a wet combustion project in the Celtic Field. Heat will be generated by burning some of the oil in the formation and water will be injected periodically. The pilot project will involve the drilling of 25 new wells. The funding for the project includes money for conducting environmental assessments and for developing new methods for processing the oil. The Celtic project has already received approval from the Saskatchewan Department of Environment and the Saskatchewan Department of Mineral Resources. A general public inquiry about the project was held prior to approval.

Current Regulations

Most of the regulations surrounding oil and gas development in Canada are developed by the provincial governments. The federal government has promulgated general air and water quality standards; but the provincial governments can amend the federal standards and usually develop stricter and more comprehensive regulations and policies. Alberta's air pollution standards are generally stringent and there is considerable concern as to how these can be reconciled with the large-scale expansion of thermal processes planned for the province's oil fields.

Alberta's groundwater reinjection regulations are also stringent. It is required that all produced water be reinjected into the same stratum from which it was drawn or into a stratum which is chemically closely akin to the original formation.

It is the practice in Alberta and Saskatchewan to hold public hearings on possible environmental and socioeconomic impacts prior to the opening of a new oil field for development or the initiation of a new oil recovery project. The Alberta provincial government has become concerned with environmental problems which potentially will be encountered with widespread thermal recovery development. However, no specific data-gathering efforts have been carried out to resolve these concerns.

SECTION 3

REVIEW OF THE LITERATURE

This section reviews the history of EOR and EGR and the attention that has been paid to the environmental aspects of enhanced oil and gas recovery. It provides a summary of generally available information pertaining to the environmental concerns of both industry and government that are associated with EOR and EGR. Specifically, several major reports have been published which address to varying extents the pollutants associated with enhanced oil and gas recovery. Each of the major publications is identified separately and reviewed in brief as part of this section. The section serves as a guide to the publications on the subject including planning and compliance documents, regulatory studies and environmental impact assessments and statements.

In the first division of this section, examples of significant pollution events associated with past or ongoing EOR and EGR projects are reviewed along with their causes and environmental impacts. Included in the second division is a summary of current predictions regarding expansion of EOR/EGR technology. Generally a steady expansion of enhanced recovery projects is expected. A correspondent increase in the need for accurate environmental data can also be expected.

Private and public sector developments are examined - private activities for several of the currently unproven technologies have been slow. To increase the rate of commercialization of new enhanced recovery methods, the government has devoted considerable resources to involvement with industry in demonstration or pilot projects. Figures 14 to 17 and Table 7 in this section illustrate present trends and projections for EOR and EGR as a whole and separately by specific technology. The commercialization potential of the gamut of EOR and EGR processes is also examined and the U.S. DOE commercialization scenarios are summarized.

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HISTORY AND PROCESS OVERVIEW

Overview

As a result of the increasing demand for crude oil after World War II, attention was given to improved management of the known oil in place, as well as to an expansion in exploration efforts. Scientists and engineers had recognized that simple techniques of improved oil recovery had potential and realized new methods could play a very important role in adding to oil reserves and reservoir productivity (API, 1961). Since the end of the war various new fluid-injection methods have been researched that provide a potential means to recover large volumes of oil left in reservoirs after conventional recovery. However, little effort has been applied to identification of environmental problems.

Steam Injection

There were documented cases of steam injection reported in the 1920's and 1930's; and apparently discovery of the technique had been made long before that. In at least one case, in the tight sands of Bradford, Pennsylvania field, the steam or hot water injection was initiated to improve injectivity of the water rather than for the purpose of increased production (API, 1961). In other situations the steam had been intended for paraffin removal from the well bore. Steam injection did not significantly progress until the 1960's when Shell Oil Company experienced success with cyclic steam soak in California (API, 1961). Since then, steam flooding has been applied successfully to heavy oils in a variety of California fields (Figures 7 and 8). At the present time, steam soak is a technically proven and economically acceptable enhanced recovery process and in some cases steam flooding looks promising. Large-scale expansion of steam soak in California is presently being held up by air pollution concerns. Various options are under consideration including use of scrubbers, low NO_x burners, fluidized-bed coal generators, solar generated steam, and revision of regulations.

There has been little concern about environmental protection until the present. Conflicts with air regulations have led to air sampling, stack sampling, air dispersion modeling, and developmental scrubber engineering. Reuse of produced water for steam injection is also under study.

In Situ Combustion

Air and water injection were common in the earlier part of the 1900's. The purpose of air injection at that date was

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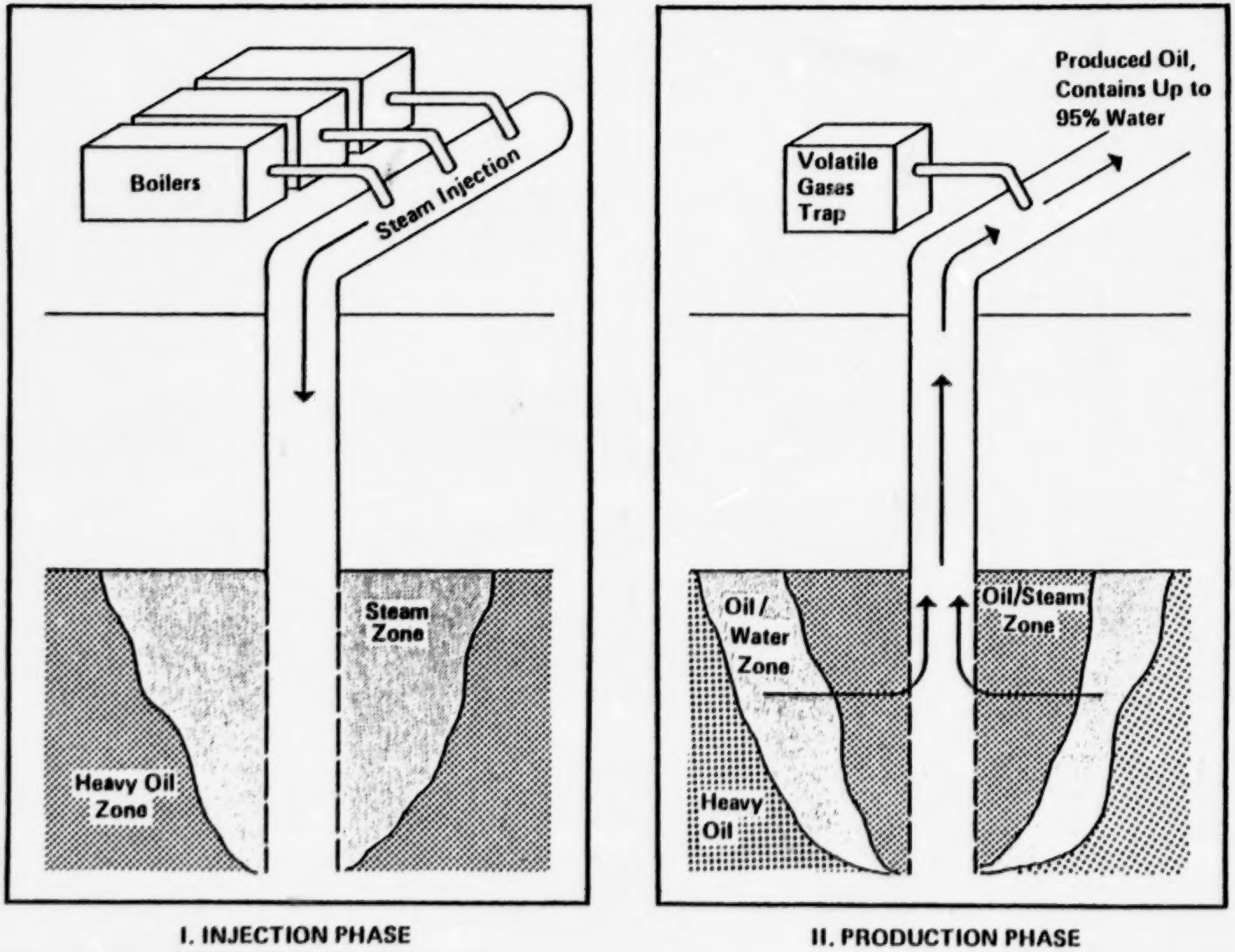
Boilers
Steam Injection
Heavy Oil Zone
Steam Zone
Volatile Gases Trap
Produced Oil, Contains Up to 95% Water
Oil / Water Zone
Oil/Steam Zone
Heavy Oil

I. INJECTION PHASE

II. PRODUCTION PHASE

Figure 7. Steam soak process.

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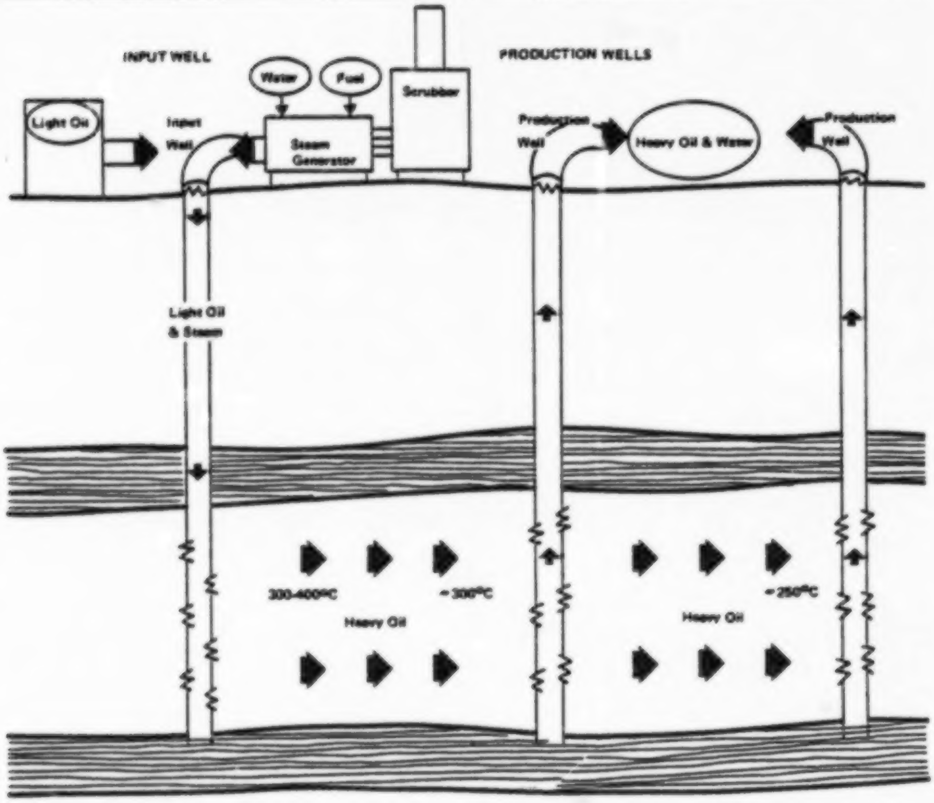
INPUT WELL
PRODUCTION WELLS
Water
Fuel
Scrubber
Light Oil
Input Well
Steam Generator
Production Well
Heavy Oil & Water
Production Well
Light Oil & Steam
300-400°C
~300°C
Heavy Oil
Heavy Oil
~250°C

Figure 8. Steam drive process.

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to "push" the oil towards the producing well. Yet produced air samples having CO_2 in them indicated that subterranean combustion had been at least partially responsible for the "air-injection" that increased production.

The Russians probably did some of the earliest work in in situ combustion EOR in 1935 in shallow, high permeability-high porosity sands. The oil laden sand was ignited by glowing charcoal (API, 1961). The Russian in situ combustion work was done in a pressure-depleted reservoir with 36 API gravity crude. The recovery was small, but significant. In situ combustion was probably unknowingly conducted in the early 1900's before it was recognized as such. The most significant present work in the United States is in California by Getty and Citgo. Figures 9 and 10 depict the process. Environmental studies have not been performed.

Improved Waterflood[33]

Simple waterflooding had its beginning over a century ago in the Bradford field of western Pennsylvania when an insufficient packer allowed leakage of shallow groundwater into a well's oil column. While the production of the immediate well was curtailed, there was a marked increase in oil production at the surrounding wells.

Early operators build on this experience and developed "circle floods" whereby they would incrementally waterflood their field by turning central producing wells into water injectors, and as oil production continued radially convert the closest watered-out producers to water injectors.

For many years waterflooding was practiced illegally in Pennsylvania (Schumacher, 1978): not until 1921 was the practice legalized in Pennsylvania. Other early waterflooding projects took place at California's Kern River field and in Ontario (IOCC, 1974), but many believed the water would contaminate or dilute the oil (Schumacher, 1978). Legislative constraints diminished in the 1940's and the practice spread to fields across the country.

Improved waterfloods or polymer-augmented waterfloods were developed in order to increase recovery efficiency of the flood. The improvement in oil displacement efficiency over and above straight waterflooding is minimal; but the polymer thickens the injected water and greatly improves the sweep conformance, causing the waterflood to affect a larger part of the reservoir. Early developments related to the effects of

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[33] Summarized from Schumacher, 1978.

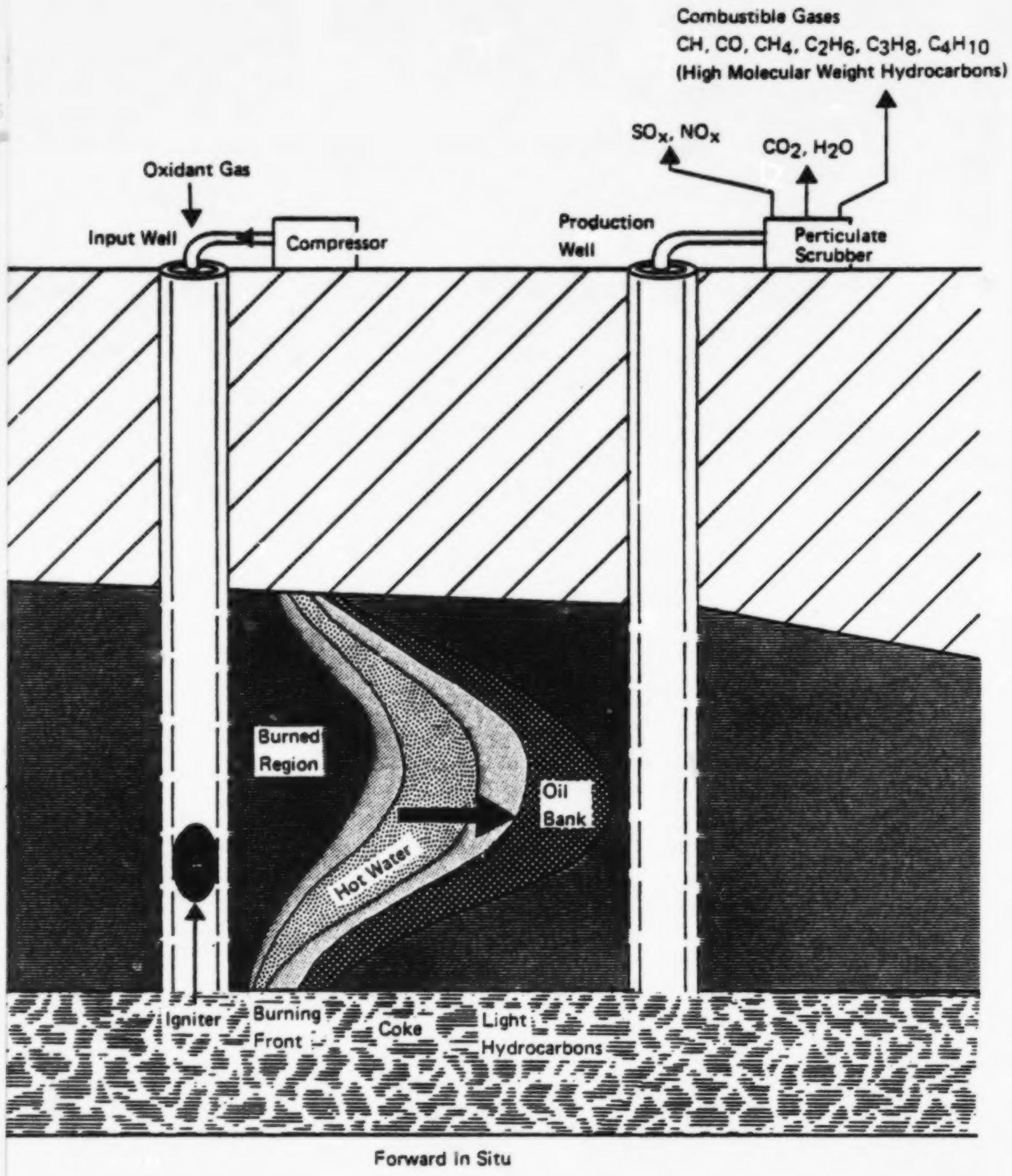
Combustible Gases
CH, CO, CH_4, C_2H_6, C_3H_8, C_4H_{10}
(High Molecular Weight Hydrocarbons)
SO_x, NO_x
CO_2, H_2O
Oxidant Gas
Input Well
Compressor
Production Well
Perticulate Scrubber
Burned Region
Oil Bank
Hot Water
Igniter
Burning Front
Coke
Light Hydrocarbons
Forward In Situ

Figure 9. Forward in situ combustion process.

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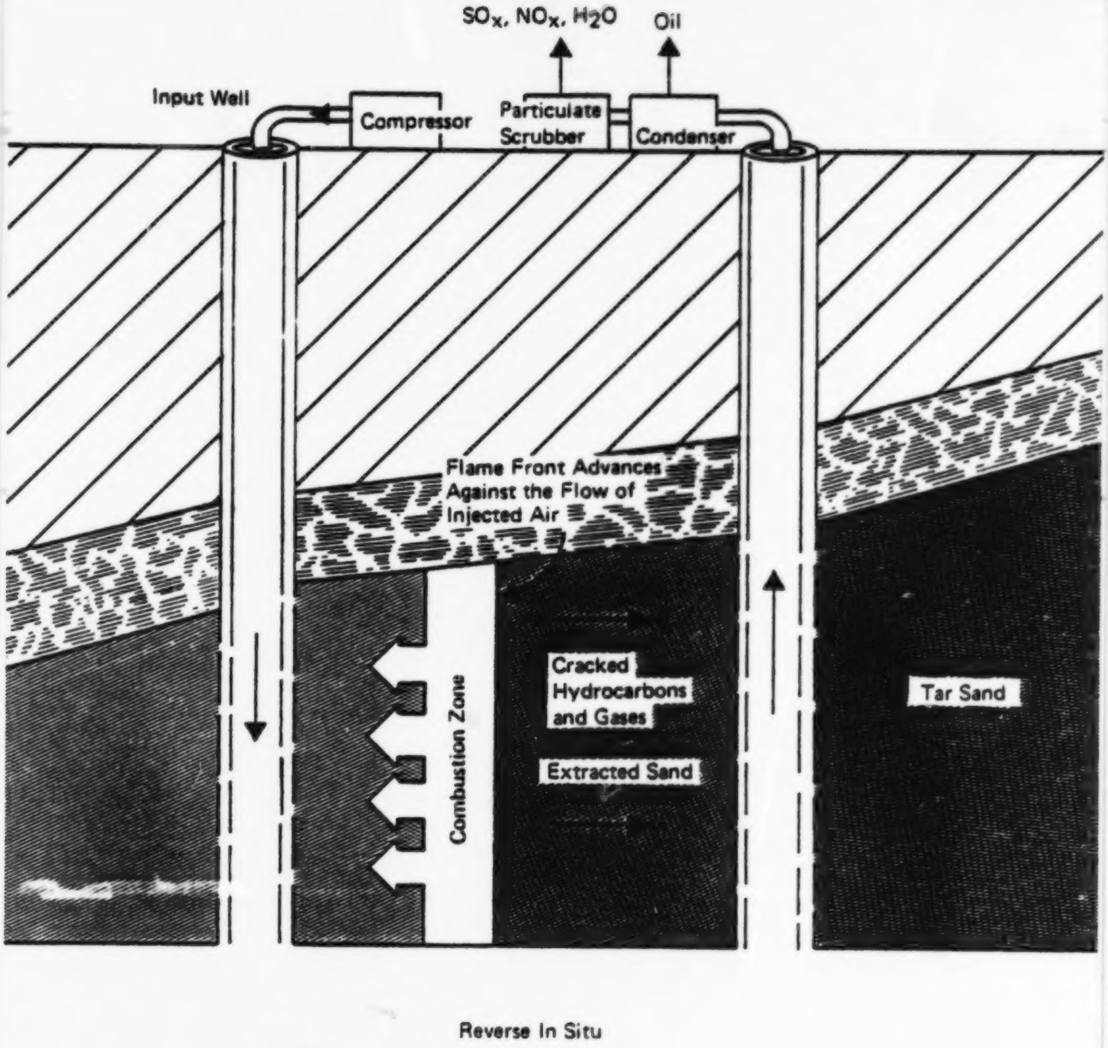
SO$_x$, NO$_x$, H$_2$O
Oil
Input Well
Compressor
Particulate Scrubber
Condenser
Flame Front Advances Against the Flow of Injected Air
Combustion Zone
Cracked Hydrocarbons and Gases
Extracted Sand
Tar Sand
Reverse In Situ

Figure 10. Reverse in situ combustion process.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

different fluid mobilities and particularly to the fluid mobility ratio of oil to water on injection and production in flood patterns (Caudle and Witt, 1959; and Barnes, 1967) proposed increasing waterflood's sweep efficiencies by increasing the viscosity of the injected water (Chang, 1978). Then in 1964 water soluble polymers were suggested as the thickening agents to be added before injection to reduce water mobility. Since that time numerous laboratory and field studies have been done to further refine the process. Improved waterfloods were field tested in the 1960's.

Regarding environmental protection, the injected chemicals are of potential concern. Historical data on polymers used in this process exist from the use of the same classes of chemicals as flocculating agents in water treatment processes. Flocculating agents have been screened for health hazards on a regular basis by the chemical manufacturers who supply them although there is no formal EPA review process nor have any detailed EPA studies been performed to evaluate use of flocculants.

Micellar/Polymer Flooding[34]

Micellar/polymer flooding involves the use of a surfactant/water injection followed by polymer/water injection. These "slugs" of fluid act to improve the displacement efficiency and sweep efficiency over a conventional waterflood. Polymer adds conformity to and enhances sweep efficiency of the surfactant slug, which acts to minimize fluid-oil interfacial tension (see Figure 11). Surfactant flooding was initiated in the late 1920's and 1930's, using polycyclic sulfonic substances and wood sulfite liquor. As the technique progressed, a range of chemical substances were considered for use as long as they achieved the desired results of reduced interfacial tension between oil and flooding fluid and prevention of excessive adsorption of the surfactants in the reservoir. A range of surfactant-solvent compounds are still used in micellar/polymer flooding today and as a result it is difficult to analyze the pollution effects from the surfactant slug.

Additional laboratory studies and refinement of the chemical flooding theories gave rise to the so-called low-tension flooding process whereby large volume (30 percent of the pore volume), low surfactant concentration (<2 percent) floods are used. In 1959 and 1961, this process was further refined by patents teaching injection of surfactant in

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[34] Gogarty reviews the development of surfactant or micellar/polymer flooding in his 1975 paper on the "Status of Surfactant or Micellar Methods" (see Gogarty, 1975).

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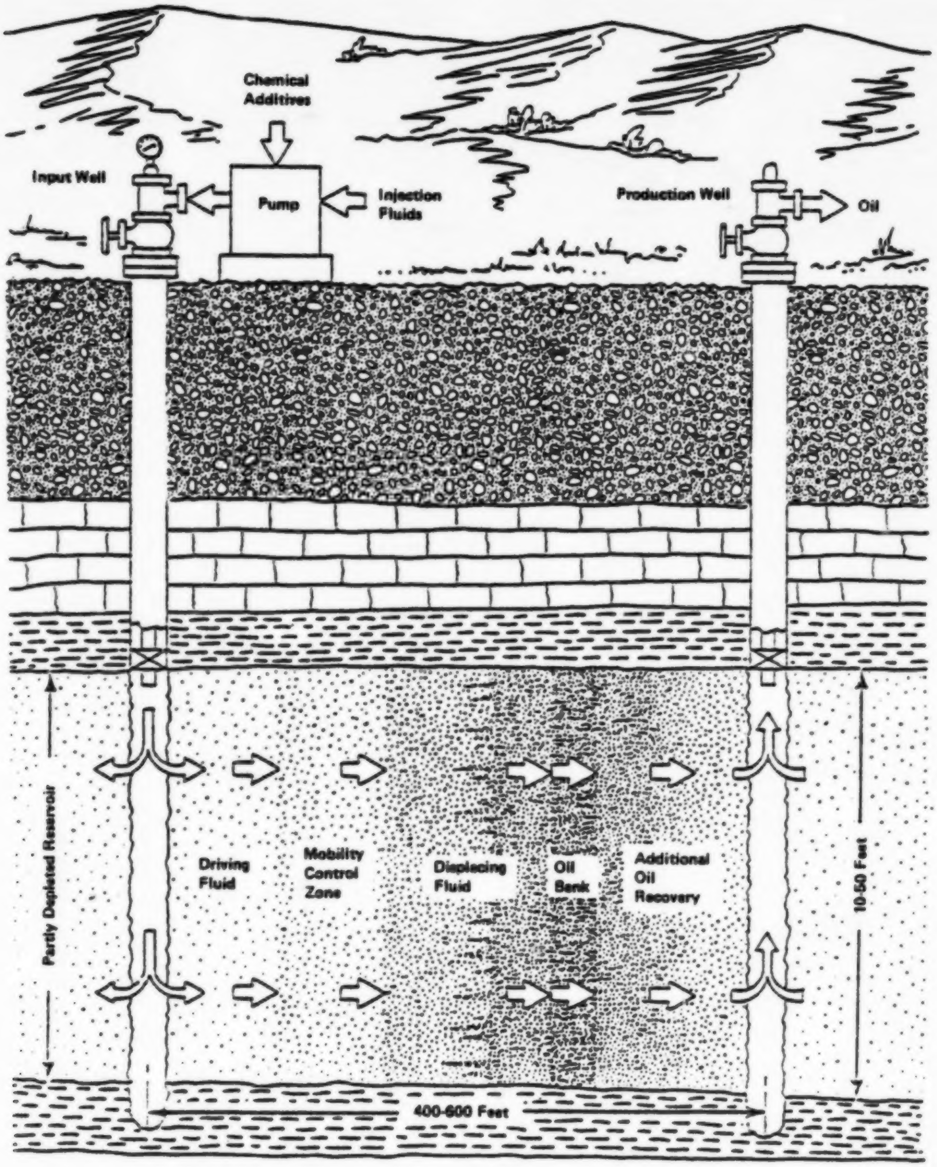
Chemical Additives
Input Well
Pump
Injection Fluids
Production Well
Oil
Partly Depleted Reservoir
Driving Fluid
Mobility Control Zone
Displacing Fluid
Oil Bank
Additional Oil Recovery
10-50 Feet
400-600 Feet

Figure 11. The micellar-polymer flooding process. (ERDA, 1975).

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EPA-287 (Cin.)
(4-76)

low-viscosity hydrocarbon solvent (Holm and Bernard) and other hydrocarbon solutions for specific reservoir conditions. The processes using petroleum-based sulfonate slugs became known as soluble oil flooding processes.

Microemulsions[35] for use in oil recovery were first patented as part of a well stimulation process to remove obstructing waxy solids. Twenty years later, what would become the well-known "Maraflood" enhanced recovery process licensed by Marathon Oil Company was introduced by Gogarty and Olsen. This process differed from the low-tension floods because a small fraction of the pore volume and a relatively high surfactant concentration (>5 percent) were used.

Several types of surfactant flooding have been developed, but generally they are of two types. In the first, large volumes (15 to 60+ percent pore volume) and low concentrations of surfactant dissolved in oil or water are injected. The second type involves a relatively small volume (3 to 20 percent pore volume) of highly concentrated surfactant.

The slug that is used in micellar/polymer floodings can have a variety of components that make assessment of its environmental hazards difficult at best. Often the exact composition of additives used is not known since crude extracts of roughly determined nature may be added. The basic composition of a micellar slug is hydrocarbon, surfactant, and/or water, and often added to those are cosurfactant (usually alcohol) and electrolytes (inorganic salts).

Alkaline Flooding

The history of alkaline flooding is most likely directly aligned with that of water flooding. After water flooidng was recognized as an effective recovery mechanism, the addition of various alkaline chemicals was considered as an option for recovery of further fractions of the remaining oil in suitable reservoirs. The alkaline chemicals were added to the drive water to enhance recovery by improving formation wettability, oil emulsification and reducing interfacial tension (U.S. DOE, 1978f).

Regarding environmental protection, the only relevant work has been a recent environmental assessment (O'Banion, 1978b).

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[35] Microemulsions - surfactant stabilized dispersion of water and hydrocarbons. The aggregates of surfactants and hydrocarbons (micelles) are in the general size range of 10^{-6} to 10^{-4} mm.

EPA-287 (Cin.)
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CO_2 Miscible Flooding

Out of the search for the development of more efficient recovery technologies, the concept of miscible fluid flooding developed, and many petroleum scientists were intrigued by the idea of miscible fluid displacement (IOCC, 1974). Although the concept of miscible fluid displacement was proposed in 1972, the idea was not tested in field applications until the late 1950's (Schumacher, 1978).

The use of CO_2 as a miscible flooding agent evolved because it was known to be one of the few low-cost fluids that could be miscible with both oil and water if the right physical conditions were maintained (Schumacher, 1978). A carbonated waterflood using this concept was initiated in the Bartlesville sand formation, Oklahoma, in 1961. From 8 to 10 pounds of CO_2 were added to each barrel of injected water. However, this application had very disappointing recovery effects, apparently due to formation fractures and peripheral stratifications that diverted the main stream of the fluid (IOCC, 1974). Apparently, though laboratory tests showed the CO_2 process to be promising and very efficient, in field applications the miscible slug of solvent becomes enriched with oil as it passes through the reservoir and loses a large part of its scavenging ability (IOCC, 1974).

Enhanced Gas Recovery

None of the enhanced gas recovery technologies are novel. Most of them were developed as mechanisms for enhanced oil recovery and have since been applied to EGR. In order to make enhanced recovery of natural gas economically sound, improved economics, reservoir characterization, well stimulation procedures, and field development techniques will be required (U.S. DOE, 1978b). The techniques are depicted in Figures 12 and 13.

Historical Occurrence of EOR/EGR Related Pollution

This section provides examples of events that have occurred or situations that exist in which enhanced recovery has resulted in environmental degradation. It is probable that significantly more degradation has occurred than is reported here. This is because there is no regulatory structure for the reporting of these events or the inspection of these projects; and events which occur may go unreported. Generally, industry and DOE sources were unwilling to disclose data regarding these events. Also, very little environmental monitoring is

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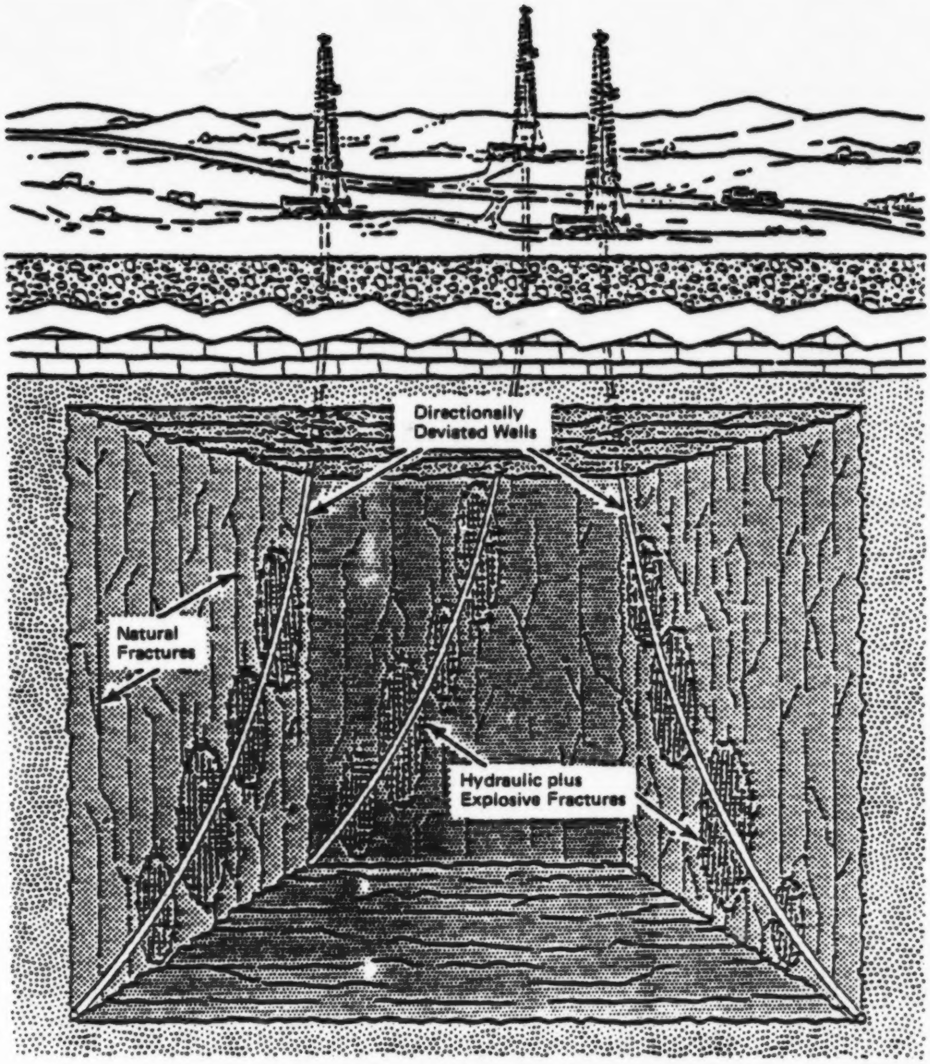
Directionally Deviated Wells
Natural Fractures
Hydraulic plus Explosive Fractures

Figure 12. Directionally deviated wells stimulated by hydraulic plus explosive fracturing. Three-dimensional cross section with cutaway area showing wells directionally drilled through natural fractures then submitted to multiple hydraulic plus explosive fracturing. (U.S. DOE, 1978e).

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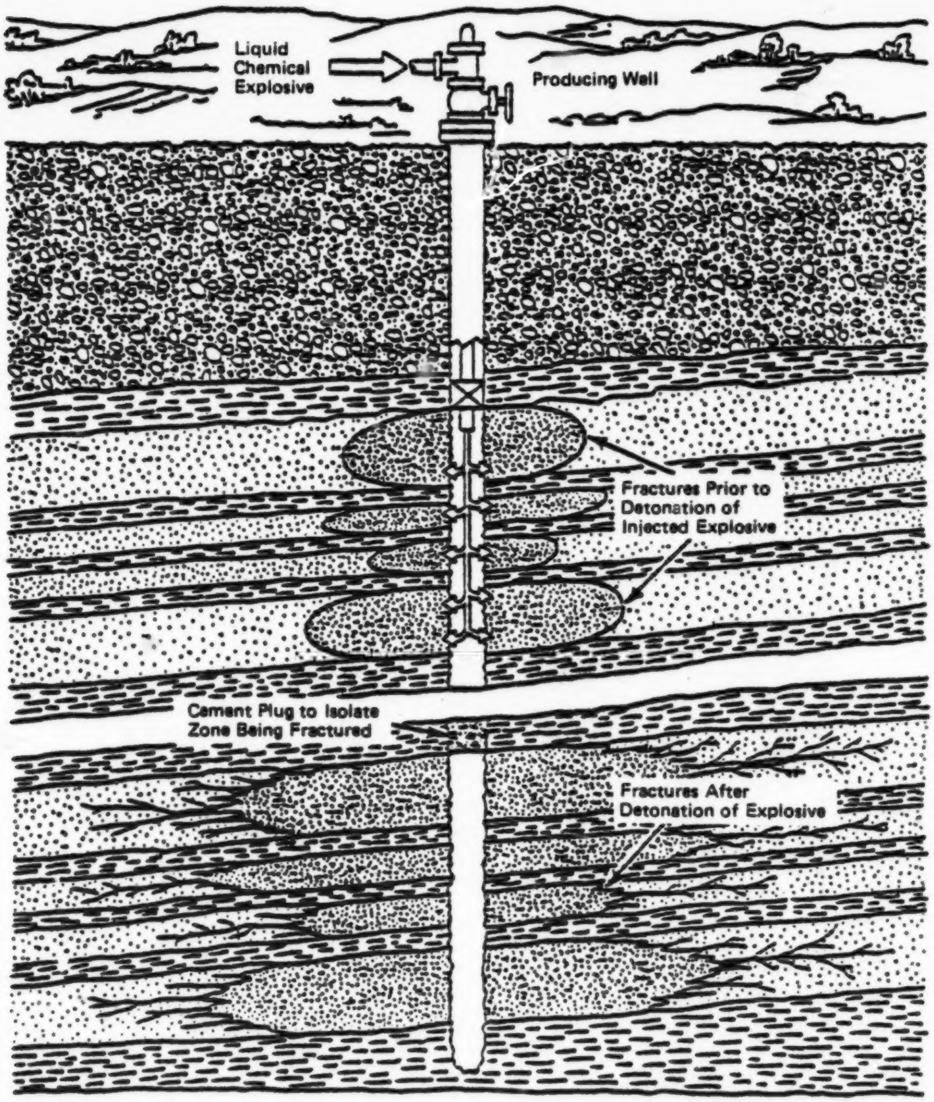
Liquid Chemical Explosive
Producing Well
Fractures Prior to Detonation of Injected Explosive
Cement Plug to Isolate Zone Being Fractured
Fractures After Detonation of Explosive

Figure 13. Chemical explosive fracturing. The injection and detonation of liquid chemical explosives increase production of petroleum from tight formations. (U.S. DOE, 1978e).

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undertaken in conjunction with enhanced recovery projects, hence pollution events may well be occurring without being detected.

One of the major problems of environmental monitoring of enhanced recovery is the undefined nature of groundwater pollution. Very little is known about the fate of fluid left in the reservoir, making it unclear where one should locate sampling stations.

The problems cited here appear to be representative of events that occur.

- Guyan Oil Company CO_2 Flood - This involves serious surficial erosion occurring at an enhanced oil recovery project operated by the Guyan Oil Company near Lincoln City, West Virginia.

- Oklahoma Vamoosa Aquifer - The Vamoosa aquifer is analyzed in a detailed study done by the U.S. Geological Survey (1978) on groundwater quality in north-central Oklahoma. The results of their study indicate that the water quality in the formation, a fresh water aquifer, may have been degraded over the years by large-scale regional oil recovery activities.

- California Steam Soaks - There is a significant problem regarding air emissions from steam soak and steam drive recovery projects in Kern and Santa Barbara Counties (OGJ, 1979).

Guyan Oil EOR Project--

Slumping occurred at the Guyan Oil Company's West Virginia EOR project. Although the problem was caused by a combination of local factors, the general soil composition of that site (high clay content and susceptible to slippage) is similar to the topography and soils encountered in much of the eastern gas and oil production in most of Appalachia. An Environmental Impact Assessment (EIA) for the project was prepared only following the event. The unstable nature of the steep slope was enhanced by the presence of a natural spring which lubricated the slip slope. The drilling activities, soil movement, weather conditions, and spring water precipitated a large-scale landslide extending from the drilling pad to the valley bottom. The delicate, densely vegetated area suffered from a variety of erosional impacts owing to construction of the drilling pad, steep switch-backed dirt roads up the mountain sites to the drilling site, and loss of top soil once vegetation was removed from certain areas.

The Department of Energy contracted the Mitre Corporation to prepare an environmental impact assessment of the project area following these events (Mitre, 1978). Suggestions that evolved from the study included erosion control, a monitoring program, the development of a directional drilling program in the area such that wells would be drilled in a cluster operation in the valley bottom. Legal action, initiated by environmentalists from outside the state, followed the event. The use of directional drilling would make it possible to reach the reservoirs that would otherwise have been drilled from environmentally detrimental mountainside positions. This type of operation would minimize surficial erosion and landsliding that occurred from the construction of drilling pads and drilling roads up on the unstable mountainside. At this time, such environmentally designed projects or techniques have not been developed in the field.

Vamoosa Aquifer--

A major controversy has evolved with opposing points of view on the cause. Two of these viewpoints are results of a USGS study and that espoused by the Interstate Oil Compact Commission. The Vamoosa aquifer, underlying large regions of Oklahoma, has been widely contaminated by brines from the extensive oil operations carried out in the region for decades.

A report evaluating the nature of the problem (USGS, 1978) infers that the rise in the base of fresh water in the Vamoosa aquifer is at least partly due to the extensive oil production within the state. One hundred water samples were taken and several hundred determinations of specific conductance were made on surface and ground waters in order to evaluate present and potential water-supply and pollution problems for that part of Oklahoma (D'Lugosz & McClafin, 1978). The major conclusion from the study was that "both surface and ground waters have been degraded locally by sodium chloride brines" (D'Lugosz & McClafin, 1978). The study also concludes that the most probable source of the NaCl brines that have polluted the aquifer is associated with the production of oil.

The report is subject to a heated controversy in the State of Oklahoma at the present time and a follow-up study is being done by D'Lugosz. The Interstate Oil Compact Commission attributes the inflated NaCl levels to the pre-1960 "evaporation pits" which existed all over the state before they were banned by law in the early 1960's.

Since the 1930's, when brines started being used for secondary oil recovery and pressure maintenance, about 995,000 acre feet have been injected in the oil producing areas of

Oklahoma (D'Lugosz & McClafin, 1978). The authors of the Vamoosa study observed indications of salt water pollution in the field (vegetation killed, salt encrustations on soil surfaces, surface oil on water in remote areas, and the increased algal growth for increased plant nutrients) and field practices detrimental to the environment (such as leaching pipes from oil wells, and release of salt water into stream gullies from surface pipes).

Five possible ways that salt water infiltration detrimentally affects the immediate environment are listed in the report:

1. Lateral leakage from corroded casing and pipes.
2. Upward movement and leakage through abandoned and improperly plugged boreholes.
3. Infiltration from surface pits, new or abandoned, that are within the recharge area of the aquifer.
4. Leakage from injection wells and upward migration of injected brines.
5. Inadequate or improper disposal of saline waters.

PROJECTIONS FOR ENHANCED OIL/GAS RECOVERY

Enhanced recovery projections have been developed by GURC (1973), the FEA (1974), Mathematica (1975), the FEA (1976), Lewin and Associates (1976), the National Petroleum Council (1976), Oil and Gas Journal (1976), and ERDA (1977). The various projections have been reviewed by Schumacher (1978).

It has been estimated that the recovery of oil from primary and secondary operations will yield only slightly more than 30 percent of the total oil in place. This leaves an additional 70 percent of the remaining oil in place as the target for enhanced oil recovery operations. The quantity of oil remaining to be discovered, the percentage of this quantity potentially recoverable, within various economic parameters; and the potential rate of production are becoming subjects of controversy as extrapolation from available information may lead to different appraisals of oil reserve potential.

For example, as of 1975: (1) the U.S. Geological Survey (USGS) officially estimated undiscovered recoverable reserves at between 110 and 114 billion barrels, (2) the National Petroleum Council (NPC) correspondingly estimated this range as 53 to 70 billion barrels, and (3) a Mobil Oil Corporation

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analysis placed recoverables at approximately 13 billion barrels. A prior study by Hubbert, a USGS geologist, estimated that only 9 billion barrels are recoverable (Schumacher, 1978). According to API estimates, proven crude oil reserves in the United States as of January 1978 amounted to 29.5 billion barrels (AGA and API, 1978).

Figure 14 displays the magnitude of the oil supply that might be available for EOR. The portion remaining as a target for enhanced recovery and the rate of that production remain highly uncertain and predictions by six firms and estimates put forth in various studies differ markedly (see Figure 15 and Table 7). Estimates of potential EOR reserves range from 15 billion barrels to 110 billion barrels within both industry and federal agency groups. Contributions of various EOR techniques to this production are shown in Table 8. Timing of EOR recovery is estimated in Figure 16. The magnitude of the difference in these opinions as to the quantity of remaining oil which can be recovered within given economic constraints reveals the basic challenge in analyzing the potential for EOR; no consensus exists as to the amount or timing of the additional oil recovery (NPC, 1978).

The Gulf Universities Research Consortium in 1973 projected that EOR methods could add 18 to 36 billion barrels of crude oil to United States proved reserves by 1985. GURC also projected a potential EOR production in 1985 of 1.0 to 1.5 million barrels per day, and an EOR cumulative production by 1985 of 1.5 to 2.0 million barrels per day beginning about 1980. The average "almost assured" forecast of 18.5 billion barrels is a reliable conservative estimate (Schumacher, 1978).

Enhanced recovery technology, if successfully and broadly applied, could significantly increase oil production from United States reserves during the years 1985-2000. Assuming continuation of historical depletion trends, production of current proved reserves (excluding the North Slope) will decline to approximately 3 million barrels per day by 1985 and to less than 1 million barrels per day in 1995-2000. Successful application of EOR technology could slow this decline during the period 1985-2000 and could exceed primary and secondary production by the late 1980's. Figure 16 outlines potential EOR producing rates in the 1980's superimposed onto the calculated decline curve of remaining primary and secondary production of current United States proved reserves (Schumacher, 1978).

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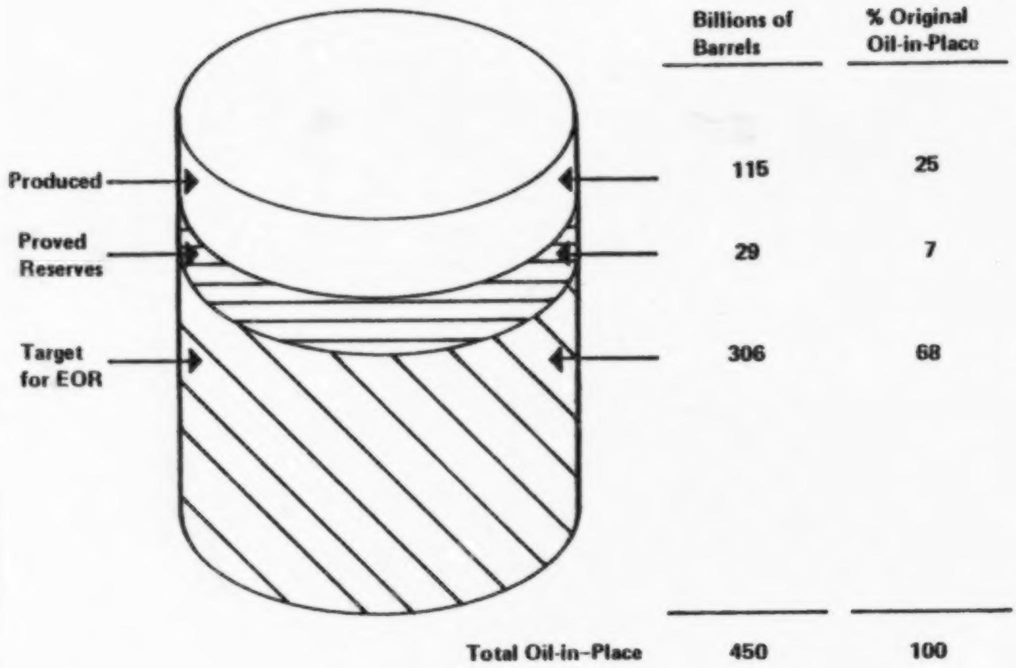

Figure 14. Production, reserves and residual oil-in-place. (API. 1978a)

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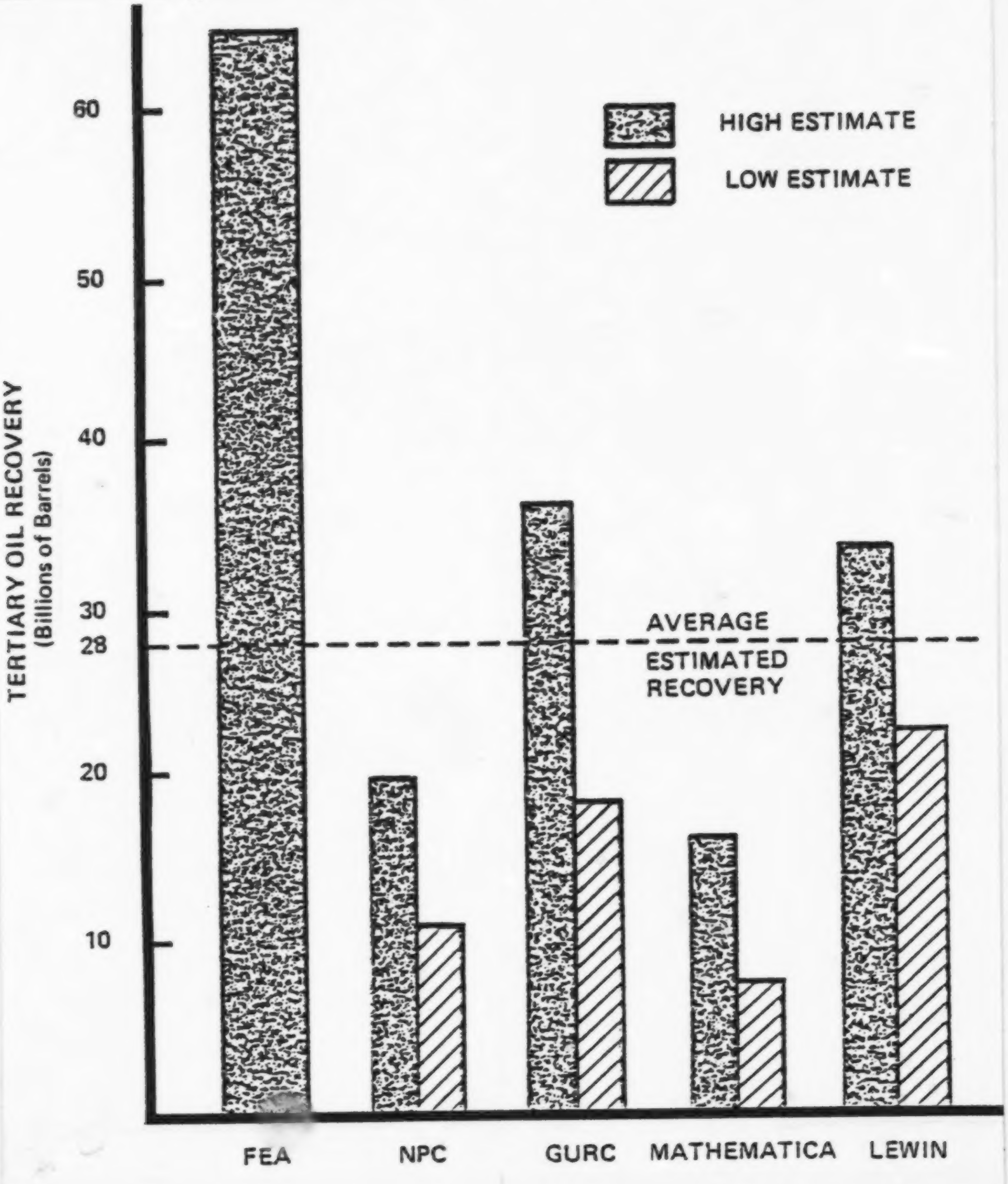

Figure 15. Forecasts of tertiary oil recovery.

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TABLE 7. ESTIMATES OF ENHANCED OIL RECOVERY POTENTIAL FOR THE YEAR 1985[a]

Fuel Cost Scenario in 1979 Dollars	Comments on the Scenario	Potential EOR Recovery (billion bbl)	Production in 1985 (million bbl/day)	Cumulative Production to 1985 (billion bbl)
1974 GURC[b,c]				
$14.29		18-36	1.1	
$21.44		51-76	-	
1974 FEA/PIR[d]				
$15.72	Business as usual	-	1.8	
$15.72	Accelerated development	-	2.3	
1975 EPA[e]				
$ 9.97-14.95		15	-	
$14.95-19.94		25	-	
1975 FEA[f] (3 states)				
$14.05 Upper bound		30.5[g]	2	
$14.05 Lower bound		15.6[h]	1	
1976 NPC Study[i]				
$ 5.94		2.2	0.3	
$11.88		7.2	0.4	
$17.82		13.2	0.9	
$23.76		20.5	1.5	
$29.70		24.0	1.7	
1976 FEA/ Energy Outlook[j]				
$14.26		-	0.9	
1978 Schumacher[k]				
	Low, of all projections	15	0.3	1.8
	Average Projection	36	1.4	3.4
	High, of all projections	100	2.7	5.9

[a] NPC, 1976. [b] GURC, 1976. [c] FEA, 1974. [d] Mathematica, 1975.

[e] Lewin, 1976.

[f] Reserves added by the year 2000 if projects return DCFROR of 20 percent or greater.

[g] Total United States; base case performance and costs; minimum DCFROR requirement of 10 percent; moderate tax case.

[h] FEA, 1976.

[i] GURC, 1973.

[j] Reserves added by the year 2000 if projects return DCFROR of 8 percent or greater.

[k] Schumacher 1978, p.11, summary of previous projections.

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EPA-287 (Cin.)
(4-76)

TABLE 8. SUMMARY OF ONGOING/PLANNED EOR PROJECTS - 1976[a]

EOR Techniques	Ongoing		Planned Conversions		Total	
	Acres	bbl/day	Acres	bbl/day	Acres	bbl/day
Steam	13,658	106,876	27,228	214,925	40,885	321,801
In situ combustion	3,984	7,581	1,164	2,212	5,148	9,793
CO_2/hydrocarbon miscible	81,925	113,500	7,100	10,000	89,025	123,500
Surfactant/polymer	758	530	189	132	947	662
Polymer/caustic	13,045	7,442	8,142	4,843	21,187	12,285
Total bbl/day from EOR		235,929		232,112		468,041

[a] Source: Oil & Gas Journal, 1976.

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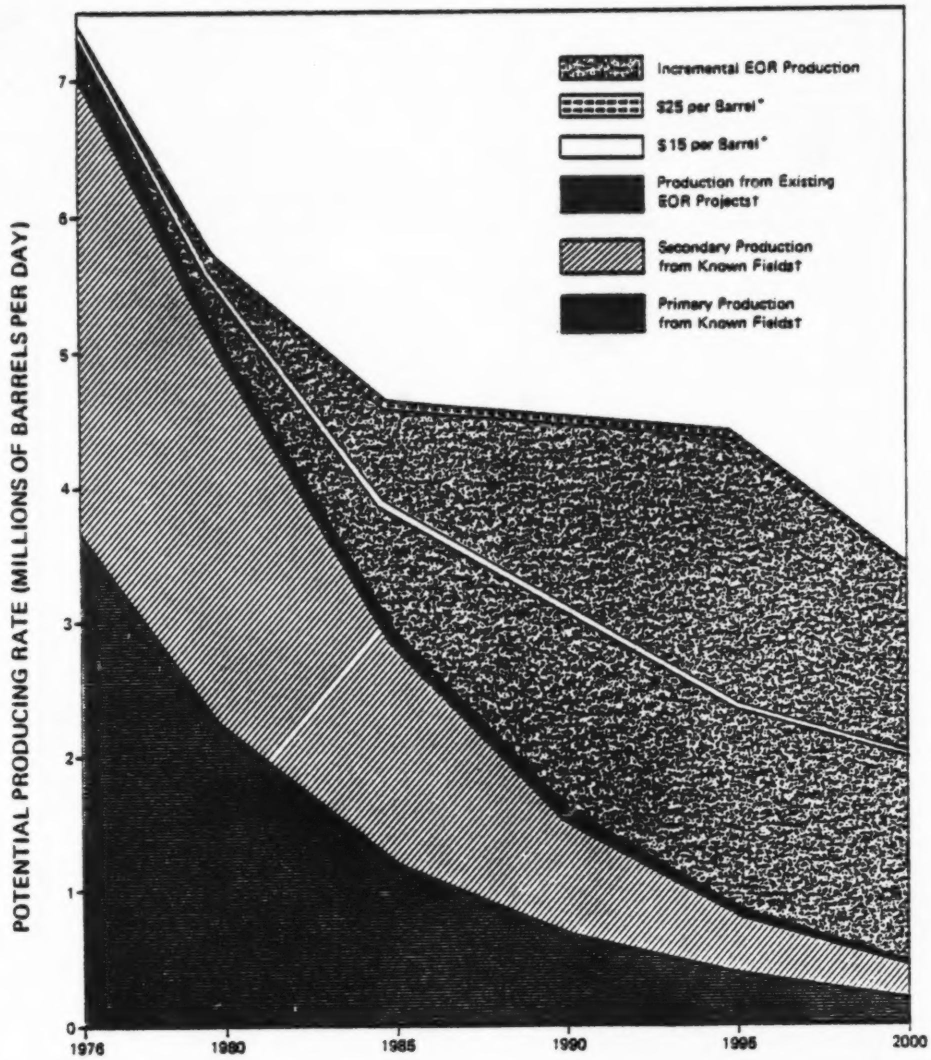

* Constant 1976 dollars and minimum DCFROR requirement—10%

† Estimated producing rates based on December 31, 1975 API reserves

Note: Production from the following sources is not considered and will be additive to the rates shown:

- Revisions except as included in API "Indicated Additional Reserves" as of December 31, 1975
- Extensions from realized enlargement of known fields
- New reservoir discoveries in known fields
- New field discoveries after December 31, 1975
- EOR from extensions, new reservoir discoveries, and new field discoveries
- North Slope, Alaska

Figure 16. Potential U.S. crude oil production rate from known fields. (National Petroleum Council, 1976).

EPA-287 (Cin.)
(4-76)

FACTORS AFFECTING COMMERCIALIZATION POTENTIAL

Issues relating to the speed of enhanced recovery commercialization and possible public roles in the process have been analyzed by two DOE studies (1978a and 1978b).

Large-scale commercialization of enhanced oil and gas recovery technologies could play a significant role in providing for near-term United States energy demands. Whether or not a particular technology is successfully commercialized will depend on a number of factors including economics, resource availability, technical feasibility, and environmental and institutional problems. The federal government has made the general policy decision to speed up commercialization of enhanced oil recovery technologies. The DOE is attempting to achieve this goal through research and development activities which will reduce technical, economic, and environmental constraints. The success with which commercialization will be achieved in the near-term will depend on the specific impediments which each technology is facing. Table 9 summarizes some of the current problems.

TABLE 9. SUMMARY OF CURRENT HURDLES TO ENHANCED RECOVERY[a]

	Economic	Technical	Environmental	Institutional
Steam drive	1	1	3	1-2
In situ combustion	2	2	3	1
CO_2 miscible	1-2	1-2	1-2	3
Micellar/polymer	3	3	3	2
Advanced waterflooding	2	2	3	2
Caustic	2	2	3	1
Massive hydraulic	1-2	1	1	1
Chemical explosive	1-2	2-3	1-2	1
Directional drilling	3	2	1	1

[a]Key: 1 = currently attractive for commercialization;
2 = most problems reduced at demonstration scale;
3 = significant problems remain.

Current windfall tax exemption provisions and recoupments will help speed commercialization. However, to date, these appear most beneficial to augmented use of the more certain technologies. Technologies still facing technical impediments,

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

such as micellar-polymer, polymer, and downhole steam injection still require DOE research and development incentives.

Oil Recovery

The EOR commercialization strategy developed by the DOE (U.S. DOE, 1978a) has two objectives: (1) to speed up development of EOR processes and (2) to increase the ultimate volume of oil recovered by EOR techniques, and in an environmentally acceptable manner. The major barrier to commercialization of techniques for construction of a new infrastructure (injection plant, chemical plant, steam generators) and/or injection of large quantities of chemicals is the unfavorable cash flows that result from high front end costs. Also, the economics have in the past often been marginal because of the complex DOE oil pricing policies. The new pricing deregulation policy, announced in April 1979, will significantly improve the economics.

Another barrier to EOR commercialization is engineering uncertainty. The inability to forecast process performance and production results in uncertain rates of return. Although there is no DOE commercialization program per se, the DOE has chosen to address this problem by a series of research-oriented demonstration projects which, if they reduce the uncertainties, can be expected to speed commercialization. In its commercialization study (U.S. DOE, 1978a), the Department of Energy estimated that full commercial development of EOR techniques, assuming certain technical advances, will provide from 30 to 40 billion barrels in additional ultimate domestic production, and that this production will generally reduce the demand for imported oil.

The Office of Technology Assessment (OTA, 1978) has prepared estimates of ultimate EOR production, with and without DOE assistance. They estimate an increase of 29.4 billion barrels in ultimate recovery through the year 2000 (under an analytical assumption of constant world prices). Some 11.1 billion barrels of EOR oil is estimated under a nonsupported (slow) process development scenario. Table 10 illustrates the effects on oil production rates. The high process development scenario entails: (1) a significant commercialization program, (2) mitigation of market constraints (pricing tiers, refinery problems), and (3) the recognition of environmental concerns.

The miscible gas and chemical flooding technologies together represented almost 50 percent of the potential production from EOR. Realization of this half of the production potential will require considerably more process development and field application since both of these processes have

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EPA-287 (Cin.)
(4-76)

TABLE 10. PREDICTED EOR YIELDS UNDER TWO COMMERCIALIZATION SCENARIOS[a]

	Ultimate Recovery (billion bbl)	Production Rate (million bbl/day)				
		1980	1985	1990	1995	2000
Low-process world price	11.1	0.3	0.5	0.7	1.2	1.7
High-process world price	29.4	0.4	1.0	1.7	3.1	5.2

[a] OTA, 1978.

received only limited field testing success. Steam flooding, which represents most of the other 50 percent, appears to have fewer outstanding technical hurdles; the major current constraints are environmental.

Technological Constraints--

Section One discussed enhanced oil production levels in 1977. The field project comprising this production met with varying degrees of success as shown in Table 11. The U.S. DOE (1978a) reports that considerable technology development is needed in order to make EOR processes constantly successful under a range of reservoir conditions. The cost of the technologies is also of concern. Commercialization of thermal and CO_2 processes will become economically feasible sooner than technologies such as surfactant polymer flooding.

Institutional Constraints--

The following institutional barriers have been identified by the U.S. DOE (1978a):

Permit Procedures. The complicated permit procedure required by local, state, and Federal agencies is of particular concern for CO_2 projects. Transportation of the CO_2 from natural sources to the project sites by pipeline will be necessary for large-scale, commercial CO_2 projects. Such pipeline construction may well encounter environmental resistance as well as complicated permitting procedures. In addition, development of large-scale projects may be delayed while the required permits and environmental assessment studies are done.

TABLE 11. OPERATING RESULTS OF EOR PROJECTS[a]

	Unknown	Successful	Promising	Discouraging
Steam Drive	11	17	14	3
In Situ Combustion	3	6	3	4
Surfactant Polymer	12	1	3	3
Polymer	5	11	5	0
Caustic	3	0	1	1
Hydrocarbon Miscible	3	6	2	1
Carbon Dioxide/Misc.	4	2	4	1

[a] Noran, 1978.

Western Water Allocations and Resource Availability. A large number of projects involving chemical flooding could be held up by an inadequate supply of injection materials.

Oil Pricing. The major institutional barriers to the development and commercialization of enhanced oil recovery is the Federal government's control of oil prices. The current movement towards deregulation of oil prices and the climbing world oil prices may both serve to alleviate this constraint. The DOE, in its commercialization strategy for EOR, recommends financial incentives for development of EOR prior to the time when EOR becomes profitable.

Gas Recovery

EGR's Potential Impact on Natural Gas Supply--

The conventional gas supply curve has continuously declined from 22.6 trillion cubic feet (Tcf) produced per year in 1973 to 19.4 Tcf in 1977. The U.S. DOE (1978b) has concluded that demand for gas will remain high and that the implementation of an active commercialization program would result in significant production from enhanced gas technologies.

In 1978 production from tight gas sands totaled about one Tcf while Devonian shale production produced approximately 100 Bcf per year in 1977. By the 1990's EGR could supply three to four Tcf per year according to DOE scenarios. Commercialization is predicted to lead to a substantial increase in the U.S. gas supply amounting to as much as six to eight Tcf per year

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

from EOR production (see Figure 17). This increase in production would come from the following unconventional gas sources:

1. The tight gas sands in the central and southwestern United States (Refer to Figure 18).
2. The Devonian shales in the Appalachian, Michigan, and Illinois basins (Refer to Figure 19).
3. Local-use, shallow coalbed methane in the eastern United States.

Commercialization of all three of these unconventional gas sources would significantly increase the nation's gas supply from 20 to 40 percent of demand by the 1990's (U.S. DOE, 1978b).

In tapping the Devonian shale resources, enforcement of non-point source pollution and sediment control regulations could limit EGR development in the Appalachian area (U.S. DOE, 1978b).

EGR Commercialization Constraints--

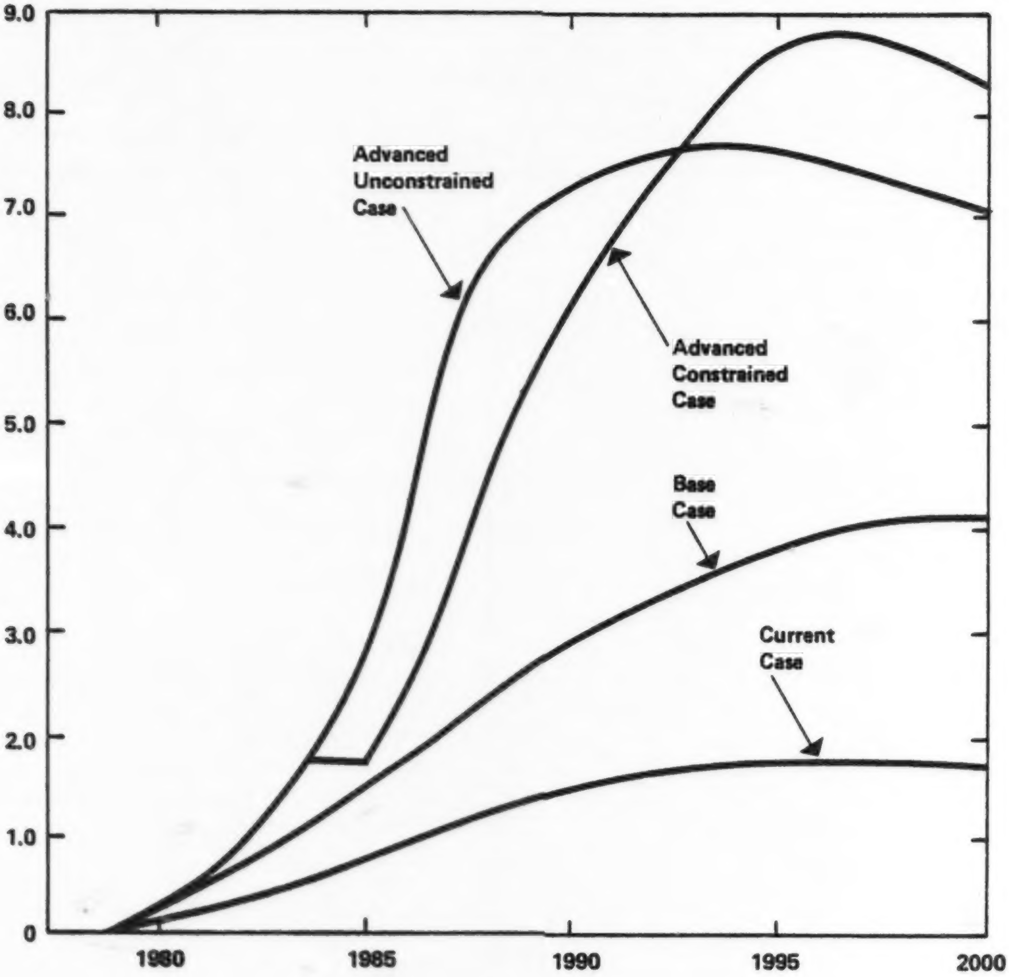
There are a variety of environmental, technical, institutional, resource availability, and economic constraints which the U.S. DOE (1978b) has associated with commercialization of EGR. These constraints are summarized and rated according to their magnitude of impact on EGR for "base case" and "advanced case" EGR development scenarios in Tables 12 and 13. See Figure 17 for description of these two cases.

ENVIRONMENTAL STUDIES OF ENHANCED RECOVERY TECHNOLOGIES

EPA Research Reports

The EPA's role in environmental control of enhanced recovery generally covers all of the pollutant sources identified in this report. The EPA's responsibility includes identification of pollutants and control options, pollutant effects research, control technology research, evaluation of costs and benefits of control options, and development of environmental control guidelines based on cost-benefit analysis. To date, EPA has seriously examined only California air quality aspects of enhanced recovery.

The 1976 report to the EPA Office of Planning and Evaluation by Energy Resources Co. (Braxton, et al., 1976) was the first EPA research carried out on the environmental aspects of EOR. The report was an overview of research priorities and provides quite a comprehensive list of the



Current case technology=Available, demonstrably reliable, current practice of the majority of producers

Base case technology=level of reliable performance predicted to result from industrys R&D efforts planned for the next five years. Assumes the removal or substantial mitigation of economic, environmental and institutional constraints.

Advanced case technology=a level of reliable performance predicated on overcoming technical constraints that industry is not expected to address before 1985. Assumes vigorous federal initiatives and removal or substantial mitigation of non-technical constraints.

Figure 17. Annual production from unconventional sources of natural gas (at NEA prices). (U.S. DOE, 1978b.)

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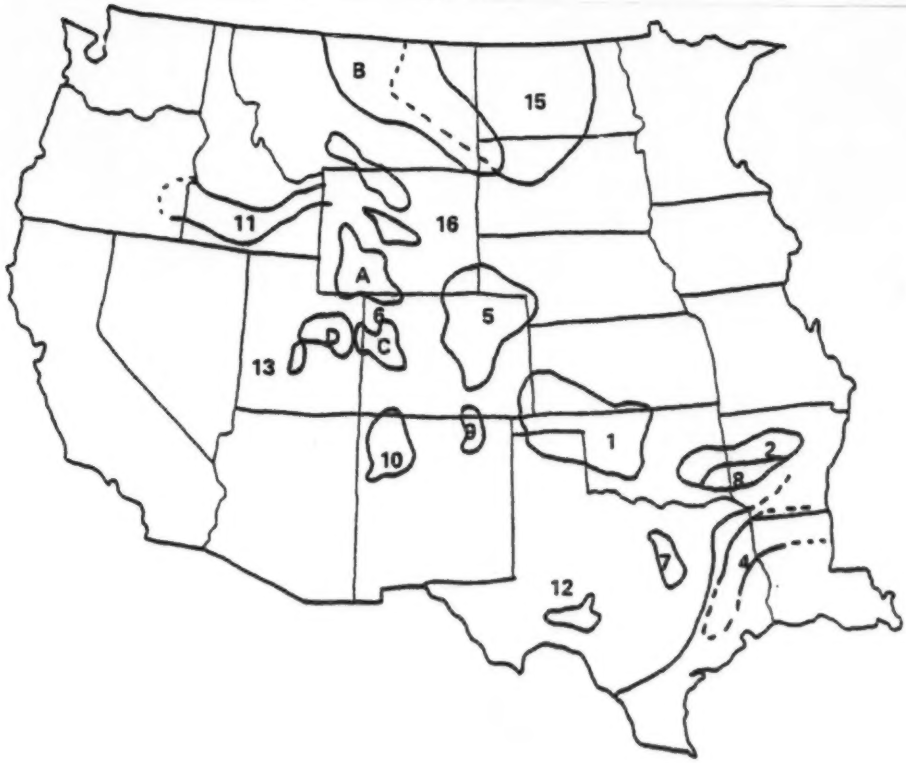

PRIMARY STUDY AREAS

A. Greater Green River Basin
B. Northern Great Plains Province
C. Plesance Basin
D. Ulinta Basin

ADDITIONAL LOW PERMEABILITY SANDSTONE AREAS

1. Anadarko Basin
2. Arkoma Basin
3. Big Horn Basin
4. Cotton Valley Trend
5. Denver Basin
6. Douglas Creek Arch
7. Fort Worth Basin
8. Ouachita Mountains Province
9. Raton Basin
10. San Juan Basin
11. Snake River Downwarp
12. Sonora Basin
13. Wasatch Plateau
14. Western Gulf Basin
15. Williston Basin
16. Wind River Basin

Figure 18. Location of unconventional gas resources in the analysis of tight gas sands. (U.S. DOE, 1978b).

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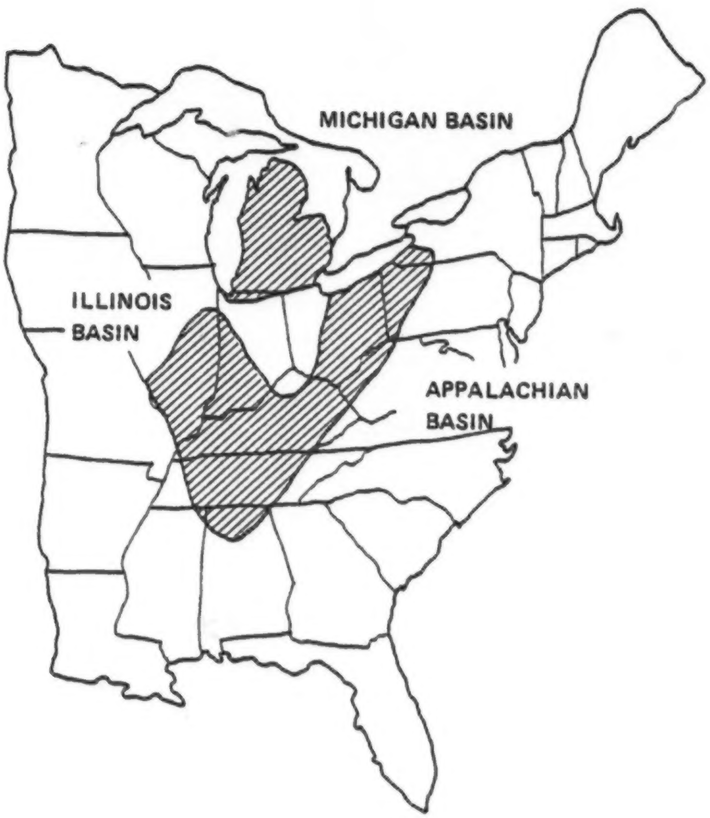
MICHIGAN BASIN
ILLINOIS BASIN
APPALACHIAN BASIN

Figure 19. Location of unconventional gas resources in the analysis of Devonian shale. (U.S. DOE, 1978b).

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PAGE NUMBER

EPA-287 (Cin.)
(4-76)

Table 12. Tight gas sands commercialization constraints.[a]

		TECHNICAL & ECONOMIC					INITIAL DEPLOYMENT			ENVIRONMENT						RESOURCE AVAILABILITY				INSTITUTIONAL		
BARRIER IMPORTANCE		5	3	4	4	3	4	2	4	3	2	1	1	1	1	1	2	1	1	3	2	2
FEDERAL ACTION		Gas Price	Potential Development Capital Limitation	Uncertain Well Production Rate (Risk)	Deficit of Reservoir Engineering Data	Lenticular & Tight Shallow: Technology Inadequate	Blanket & Near Conventional Shallow: Technology Inadequate	Potential Risk Capital Limitation	Limited Knowledge of Resource Potential	Impact of Pipelines	Water Contamination	Noise Pollution	Worker Safety	Air Quality	Site Preparation/ Restoration	Drilling Rigs	Well-Service Capacity	Water Availability	Well Equipment	Pipeline Delay-GF, GN	Drilling Permitting GF, GN	Leasing Procedures-GF, GN
INFORMATION	Assess Potential of the Resource			2	2	3	3		4							2	2		2	2		3
	Instrumentation and Diagnostic Technology	3	2	3	5	4	4	2	4													
	Field-Based R&D	3		4	3	2	5		3		2	2	2	2	2	2	2		2			
	Economic Demonstration	3	4	3	2	4	4	3			2	2	2	2	2	2	2		2			
	Optimization of Demonstration	3	3	4	3	5	3	2			2	2	2	2	2	2	2		2			
	Technology Transfer	3	3	4	3	4	4	3	3		2	2	2	2	2	3	3		3	2		2
REGULATION	Develop EA, EIS		2					2		4	4	4	4	4	4			3		3	3	3
	Assist FERC in Pricing	3	3					3								2	2		2			
FINANCIAL INCN INCENTIVES	Implement NEA	5	4					4								2	2		2			
	Cost Sharing					4	4	4												3		
	Define Need for Additional Incentives	4	3					3								3	3		3			
COORDINATION	Interagency Collaboration								3	3	3	3	3	3	3			3		3	3	3
	Monitor Resource Availability															3	3	3	3			
	Assist State/Local Community Program					2	2		3									3		3	3	3
										3										4		

[a]U.S. DOE, 1978b

Table 13. Devonian shales UGR commercialization constraints.[a]

		TECHNICAL & ECONOMIC						INITIATE DEPLOYMENT		ENVIRONMENT						RESOURCE AVAILABILITY				INSTITUTIONAL		
	BARRIER IMPORTANCE	5	3	4	4	4	4	2	4	2	2	1	1	1	3	4	2	1	1	2	1	1
	FEDERAL ACTION	Gas Price	Potential Development Capital Limitation	Uncertain Well Production Rate (Risk)	Deficit of Reservoir Engineering Data	Location of Natural Fracture Systems	Low Per-Well Production	Potential Risk Capital Limitation	Limited Knowledge of Resource Potential	Impact of Pipelines	Water Contamination	Noise Pollution	Worker Safety	Air Quality	Site Preparation/Restoration	Drilling Rigs	Well-Service Capacity	Water Availability	Well Equipment	Pipeline Delay-GF, GN	Drilling Permitting-GF, GN	Leasing Procedures-GF, GN
INFORMATION	Assess Potential of the Resources			2	2	4			4							2	2		2	2		2
	Instrumentation and Diagnostic Technology	3	2	3	4	3	2	2	3													
	Field-Based R&D Field Bases	3		4	3		4		2		2	2	2	2	2	2	2		2			
	Economic Demonstration	3	4	3	2		3	3			2	2	2	2	2	2	2		2			
	Optimization of Development (RA)	3	3	4	2	3	4	2			2	2	2	2	2	2	2		2			
	Technology Transfer	3	3	4	3	3	2	3	3		2	2	2	2	2	3	3		3	2		2
REG	Develop EA, EIS		2					2		3	4	4	4	4	4			2		3	3	3
FINANCIAL TAX INCENTIVES	Implement NEA	4	4					4								2	2		2			
	Cost Sharing (RA/ET)						3	4												3		
	Define Need for Additional Incentives	4	3					3								2	2		2			
COORDINATION	Interagency Collaboration								3	3	3	3	3	3	3			3		3	3	3
	Monitor Resource Availability															3	3	3	3			
	Assist State/Local Community Program			2	3				3									3		3	3	3

[a]U.S. DOE, 1978b

types of environmental problems that may occur. The study provided a preliminary review of the potential environmental hazards associated with EOR technologies. The processes are ranked in terms of relative potential environmental problems. A risk analysis, delineating various factors that determine probability of contamination of groundwater surrounding EOR sites and the seriousness of various leaks, is also presented. Perhaps the most significant material included in the report is the list of EOR chemicals which is the source material for a variety of subsequent efforts.

Two development documents, the development document for the Synthetic Polymers (U.S. EPA, 1975a) and the Synthetic Resins (U.S. EPA, 1975a) segments of the Plastics and Synthetic Materials Manufacturing Point Source Category, review manufacturing processes relevant to EOR. However, few, if any, specific EOR chemical manufacturing processes are considered specifically in these documents. These documents do summarize the common effluents resulting from the manufacture of polymers, in general, and do specifically cover polyamides and ethylene vinyl acetate copolymers, which are a few of the many chemicals utilized by EOR processes. Further study of the relevant chemical processes will be required if EOR processes are to be applied on a large scale.

A major problem in evaluating the potential environmental effects of enhanced oil and gas recovery is the unavailability of a complete list of the substances used in enhanced recovery techniques and knowledge of their chemical identity. In the 1976 study by Braxton et al., a list of EOR chemicals was compiled from a review of U.S. patents and literature. Further development of this list will be required.

Even if a source list is agreed upon, adequate toxicological data is still lacking. Few of the chemicals found on the list can be found in EPA water quality criteria studies or in EPA toxic substances reviews. As will be seen in Section Four of this report, toxicological studies in the open literature are scanty.

A 1979 report to the EPA Office of Policy Planning investigated environmental impediments to the development of heavy oil in California (Bennett et al., 1979a). The study assembled a database by California field of possible regulatory impediments. Related work (Bennett et al., 1979b) specifically investigated the economics of operating Getty's Kern River steam projects with SO_x scrubbers.

DOE Research Compliance Reports

The DOE has developed an approach intended to facilitate compliance of enhanced recovery technologies with environmental regulations. This approach has been presented through a series of planning documents (U.S. DOE, 1978d,e,f,g, 1979a,b; Donaldson, 1978; Booz, Allen & Hamilton, 1978; and Dalton, Dalton, Little & Newport, 1978) and a series of environmental assessments of DOE cost-shared demonstration projects (by Mitre, Oak Ridge National Laboratory, and Lawrence Livermore Laboratory).

DOE Environmental Strategy--

Two Environmental Readiness Documents, one for Enhanced Oil Recovery (U.S. DOE, 1978d) and one for Enhanced Gas Recovery (U.S. DOE, 1978c), present an overview of the current DOE approach. These documents examine, from the DOE's point of view, the environmental acceptability of enhanced oil and enhanced gas recovery. Although most approaches to problems outlined in these documents only involve evaluation of the potential problem in EIA's and EIS's, the documents do recognize the main environmental concerns surrounding EOR and EGR.

Major environmental concerns outlined in the Readiness Documents include:

1. Degradation of air quality and ability to meet Federal and local standards;
2. Water availability vis-a-vis the large quantities of water required by EOR processes;
3. Aquifer contamination, primarily related to micellar or other chemical injection techniques wherein chemicals dissipate into other rock strata.

The degradation of air quality concern is particularly addressed as per the State of California and thermal operations there. Air pollution, consisting of SO_x, NO_x, particulates, and other pollutants from steam generators used in thermal operations, is one of the major EOR pollution concerns in nonattainment areas. Thermal steam drive recovery accounts for 68 percent of all EOR oil currently being produced, hence the assessment of thermal process air quality is very important to EOR development as a whole. Also considered in the readiness document is air pollution resulting from the release of HC and H_2S gases during fireflood and CO_2 flood operations.

The physical and institutional availability of water is listed as a potential problem with EOR development, especially

EPA-287 (Cin.)
(4-76)

in western and mid-continental regions, and the DOE plans to evaluate the extent to which this will affect EOR development in a programmatic Environmental Assessment. The preliminary conclusion is that if in the future, state or local governments designate the water needs for various EOR processes as low priority, commercialization of enhanced recovery technologies could be seriously hampered.

The DOE Readiness Document recognizes many of the same groundwater pollution concerns that this study and other researchers on the subject have expressed. The DOE is currently addressing one of these concerns: Bartlesville Energy Technology Center has initiated an evaluation of all chemical work done to date on the carcinogenicity and toxicity of micellar chemicals (Silvestro and Desmarais, 1980). At the conclusion of this study, DOE's Office of the Environment intends to develop a project to determine the toxicity and carcinogenicity/mutagenicity of those chemicals not yet investigated. Further research covering other areas of concern is planned (Donaldson, 1978).

The Environmental Readiness Document on EGR predicts that several areas of environmental uncertainty will persist as EGR of western tight gas sands and Devonian shales is pushed towards commercial scale and further environmental research is done.

The following environmental uncertainties were identified to be of prime concern in the Environmental Readiness Assessment of EGR:

- The potential for surface water contamination during initial preparation and drilling operations;
- Air pollution caused by emissions from equipment and activities (diesel engines and dust) involved in site preparation and initial stimulation;
- Potential water contamination resulting from the disposal of produced residues from chemical explosives and gelled and/or decomposed fracture fluids;
- Environmental impact of the estimated 3300 miles of pipeline that will be required to transport gas from new sources; and
- Compliance with site reclamation requirements.

Efforts that the DOE plans to make in order to resolve some of these uncertainties include both site specific

EPA-287 (Cin.)
(4-76)

environmental assessments and the environmental assessments for pipeline construction. The majority of DOE's environmental research and development work in EGR, as outlined in this document, will be aimed at characterizing and assessing the potential impacts of contamination from EGR materials and decomposition products. The environmental readiness document estimated that there is a high probability of finding some EGR material or practices to be environmentally unacceptable. However, the DOE does not foresee a resulting curtailment of EGR development but rather mitigation of the adverse predicted impacts by changing or discontinuing use of the detrimental material or activity or by pollution controls.

A more detailed and specific project planning document for environmental compliance was developed by the Bartlesville Research Laboratory (Donaldson, 1978). The Environmental Compliance Project Planning Document outlined the following activities:

- Project management that will provide assistance and guidance in environmental affairs for all EOR projects and coordinate results of project research, resolving environmental impediments, identifying insurmountable environmental barriers, and consequently redirecting EOR technology development;

- Comprehensive data base development including EOR environmental regulations studies, data base acquisition, and data analyses;

- Applied research activities in the laboratory to study EOR chemicals, their reactions under reservoir conditions, and potential for pollution including reservoir modeling to determine pollutant pathways;

- Field based activities that include the development of criteria and specifications for environmental impact evaluation and the monitoring of baseline and environmental variations in EOR technologies; and

- Supporting research including development of guidelines and manuals for spill prevention and other on-site operations as well as the economic analysis of various environmental compliance options.

Environmental Assessments--

Assessments are in preparation for all DOE cost-shared projects. These assessments which have been released cover all points required by NEPA. These reports are designed to provide a brief summary of possible problems; few data are developed

EPA-287 (Cin.)
(4-76)

regarding the specific engineering, specific pollutants, and specific environmental setting of the projects. The groundwater quality issue is not considered.

Monitoring Guidelines--

Monitoring guidelines were developed based on existing regulations and toxic substances lists (Booz, Allen & Hamilton, 1978). The monitoring priorities developed in the report are open to question because of problems with the selection criteria employed.

California Air Resources Board Report (CARB)

The California Air Resources Board has carried out substantial research regarding control of SO_x, NO_x, hydrocarbon, and particulate emissions associated with heavy oil production. The various research reports have been entered as testimony in a series of CARB hearings in Kern County. The testimony mainly documents the volume of pollutants emitted, calculates cost of installing scrubbers, and attempts to demonstrate that SO_x scrubber and low NO_x burner technologies successfully comply with their Kern County regulations.

Industry Studies

Environmental issues associated with EOR have not been studied comprehensively by the oil and gas industry. Attention has been focused on those environmental concerns that may be an immediate impediment to expansion of enhanced recovery activities; namely air pollution regulations constraining the use of oil-fired steam generators in California, underground injection regulations that may increase costs associated with chemical injection, and RCRA special wastes controls that may constrain the ability to reinject brines and pond drilling muds. The study of air emissions in Kern County, California commissioned by a group of Kern County operators (Sheridan et al., 1977) provides the most detailed analysis available on the magnitudes of air quality degradation that may be expected from thermal recovery activities. The Sheridan study included an assembly of new monitoring data and air pollutant dispersion modeling. The study concluded that impacts were minimal except on unpopulated oil company owned properties. These data were also presented in an environmental impact report format to the county of San Luis Obispo (SAI, 1978). The API has devoted considerable resources to the estimation of economic impacts of various injection regulations and has prepared information to rebut EPA estimates on the economic costs of complying with proposed underground injection regulations and on designating drilling muds and oilfield brines as special wastes. The oil and gas industries have provided a variety of similar testimony at federal hearings and at industry and research symposia. Minimal environmental monitoring and analysis beyond the Kern County air quality study has been undertaken.

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SECTION 4

IDENTIFICATION OF ENVIRONMENTAL IMPACTS

This section of the report evaluates available data on enhanced recovery pollutants, their environmental fates, and their level of hazard. The first part of the section develops process flow sheets for the various technologies and identifies the various sources of pollution. The subsequent sections evaluate various environmental problems: air quality, noise, water supply, groundwater quality, enhanced gas recovery contamination, and secondary impacts.

OVERVIEW OF ENVIRONMENTAL RISKS DUE TO ENHANCED RECOVERY POLLUTANTS

Enhanced recovery operations involve the injection of a variety of synthetic chemicals into the subsurface regime. Even in heavily developed oilfields, there is considerable uncertainty regarding the detailed structure of the subsurface formations. Therefore, the fates of injected chemicals by mass balances are not completely accounted for. In particular, chemicals degrade, they migrate via old incompletely sealed-off wells, they move through fractures and they chemically interact with the rocks and soils. Associated with the various injection activities is the requirement for large volumes of water and chemicals and moderate requirements for heating in steam injection processes. These impose a variety of resource constraints and air quality degradation. Large volumes of brines are produced along with the oil and these must be disposed of. To a lesser extent the various activities associated with enhanced recovery generate noise, surface water, solid waste, and secondary demographic/ social impacts.

Process Flow Sheets

In order to define and organize the range of potential environmental problems for each technology, process flow sheets have been developed. These identify points in the process at which pollutant sources are generated. Figures 20 through 25 present the process flow sheets. Figure 22 covers all of the chemical injection processes, that is, advanced

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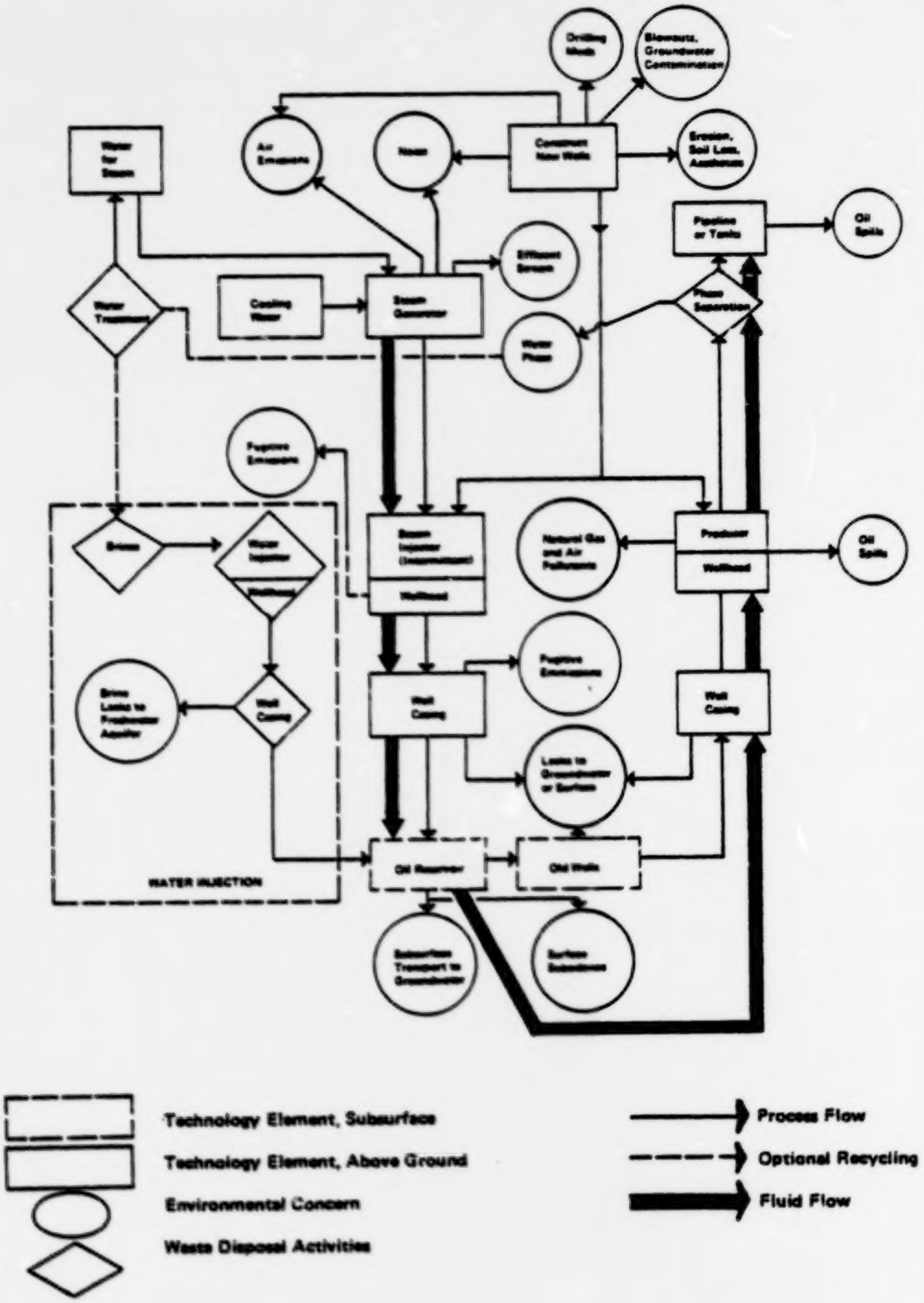
Drilling Muds
Blowouts, Groundwater Contamination
Air Emissions
Noise
Construct New Wells
Erosion, Soil Loss, Aesthetics
Water for Steam
Pipeline or Tanks
Oil Spills
Effluent Stream
Water Treatment
Cooling Water
Steam Generator
Phase Separation
Water Phase
Fugitive Emissions
Steam Injector (Intermittent)
Wellhead
Natural Gas and Air Pollutants
Producer
Wellhead
Oil Spills
Brines
Water Injector
Wellhead
Brine Leaks to Freshwater Aquifer
Well Casing
Well Casing
Fugitive Emissions
Well Casing
Leaks to Groundwater or Surface
Oil Reservoir
Old Wells
WATER INJECTION
Subsurface Transport to Groundwater
Surface Subsidence
Technology Element, Subsurface
Technology Element, Above Ground
Environmental Concern
Waste Disposal Activities
Process Flow
Optional Recycling
Fluid Flow

Figure 20. Process/Pollutant flow sheet, steam drive.

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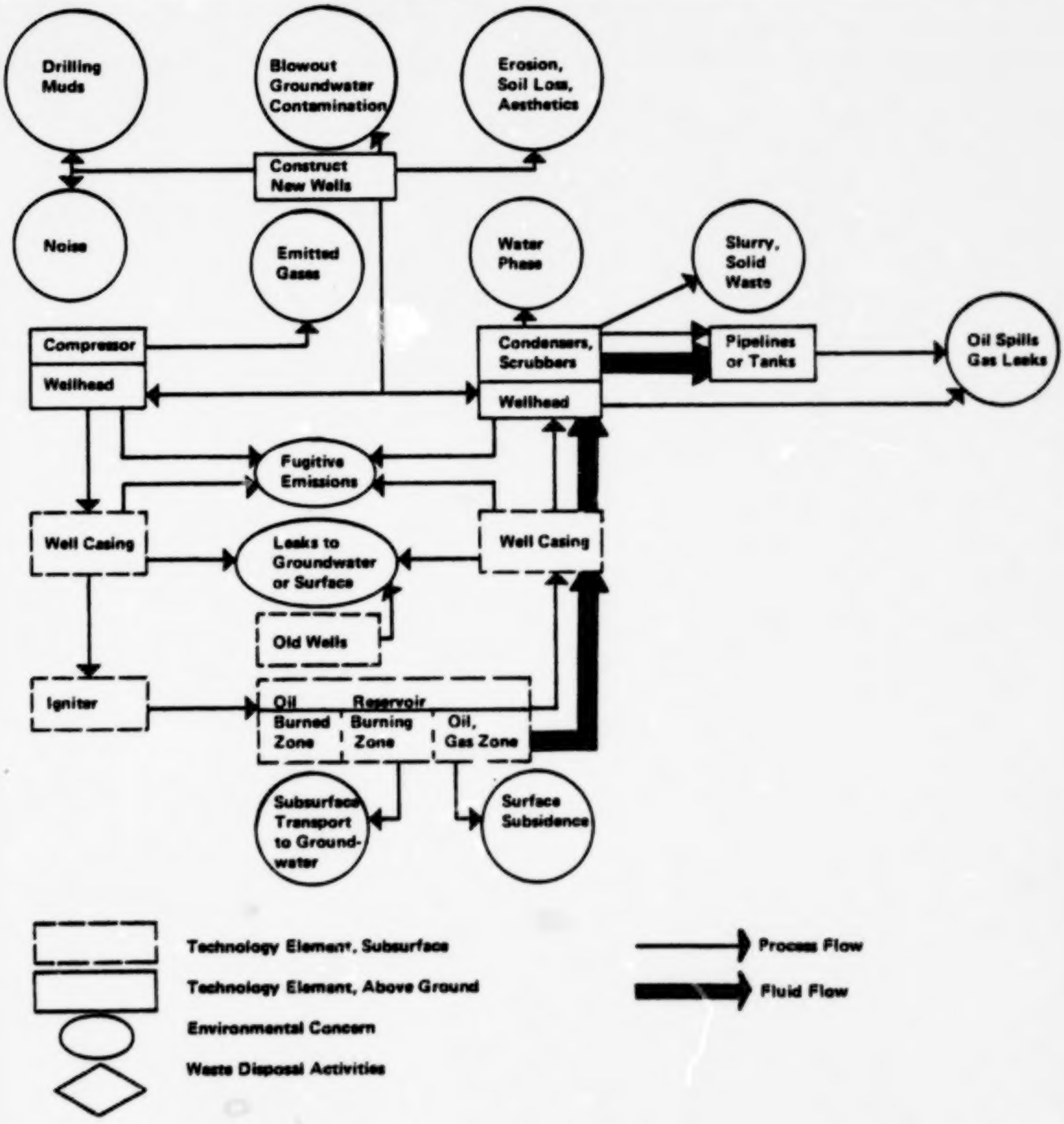
Drilling Muds
Blowout Groundwater Contamination
Erosion, Soil Loss, Aesthetics
Construct New Wells
Noise
Emitted Gases
Water Phase
Slurry, Solid Waste
Compressor
Wellhead
Condensers, Scrubbers
Wellhead
Pipelines or Tanks
Oil Spills Gas Leaks
Fugitive Emissions
Well Casing
Leaks to Groundwater or Surface
Well Casing
Old Wells
Igniter
Oil Reservoir
Burned Zone
Burning Zone
Oil, Gas Zone
Subsurface Transport to Groundwater
Surface Subsidence
Technology Element, Subsurface
Technology Element, Above Ground
Environmental Concern
Waste Disposal Activities
Process Flow
Fluid Flow

Figure 21. Process flow sheet, forward in situ combustion.

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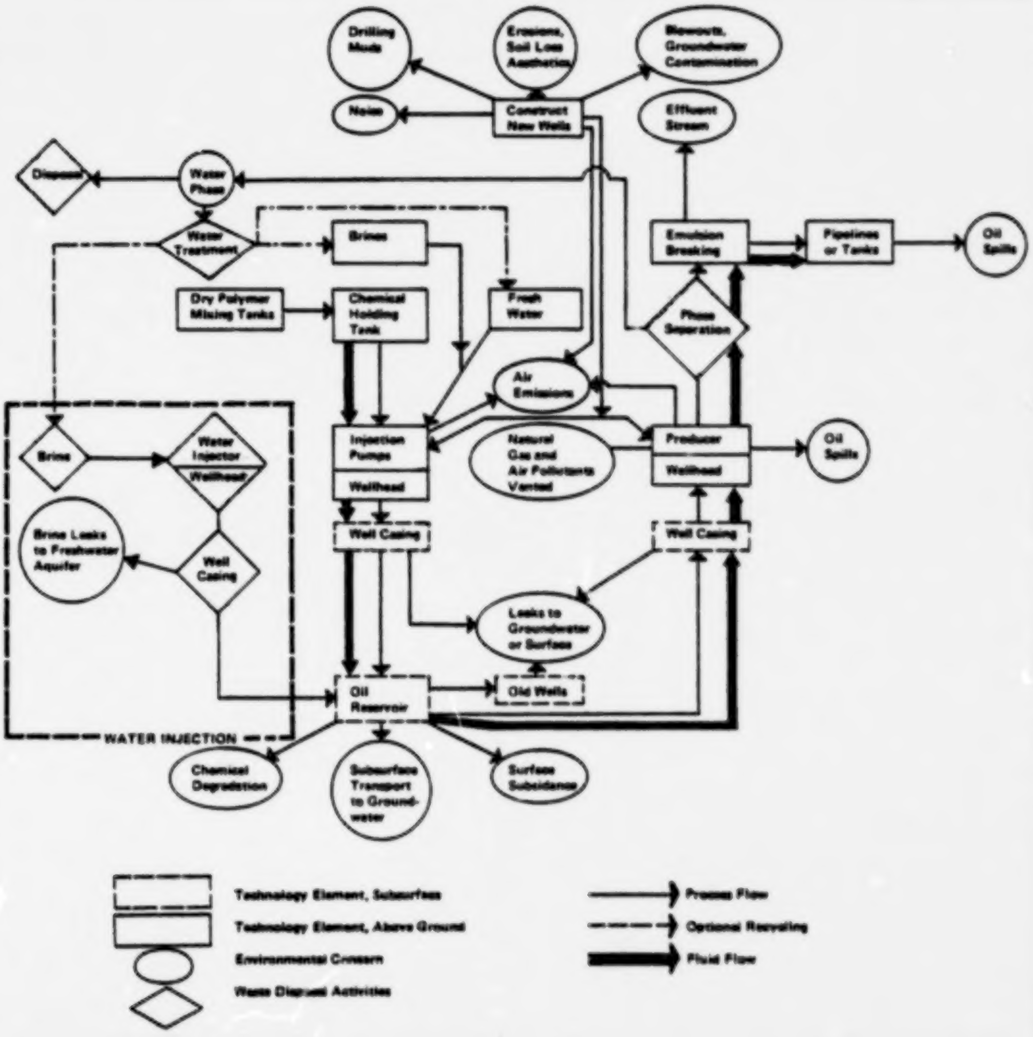
Drilling Muds
Erosions, Soil Loss Aesthetics
Blowouts, Groundwater Contamination
Noise
Construct New Wells
Effluent Stream
Disposal
Water Phase
Water Treatment
Brines
Fresh Water
Dry Polymer Mixing Tanks
Chemical Holding Tank
Emulsion Breaking
Pipelines or Tanks
Oil Spills
Phase Separation
Air Emissions
Injection Pumps
Wellhead
Natural Gas and Air Pollutants Vented
Producer
Wellhead
Oil Spills
Brine
Water Injector
Wellhead
Brine Leaks to Freshwater Aquifer
Well Casing
Well Casing
Well Casing
Leaks to Groundwater or Surface
Oil Reservoir
Old Wells
WATER INJECTION
Chemical Degradation
Subsurface Transport to Ground-water
Surface Subsidence
Technology Element, Subsurface
Technology Element, Above Ground
Environmental Concern
Waste Disposal Activities
Process Flow
Optional Recycling
Fluid Flow

Figure 22. Process/pollutant flow sheet, polymer, micellar/polymer, alkaline flooding processes.

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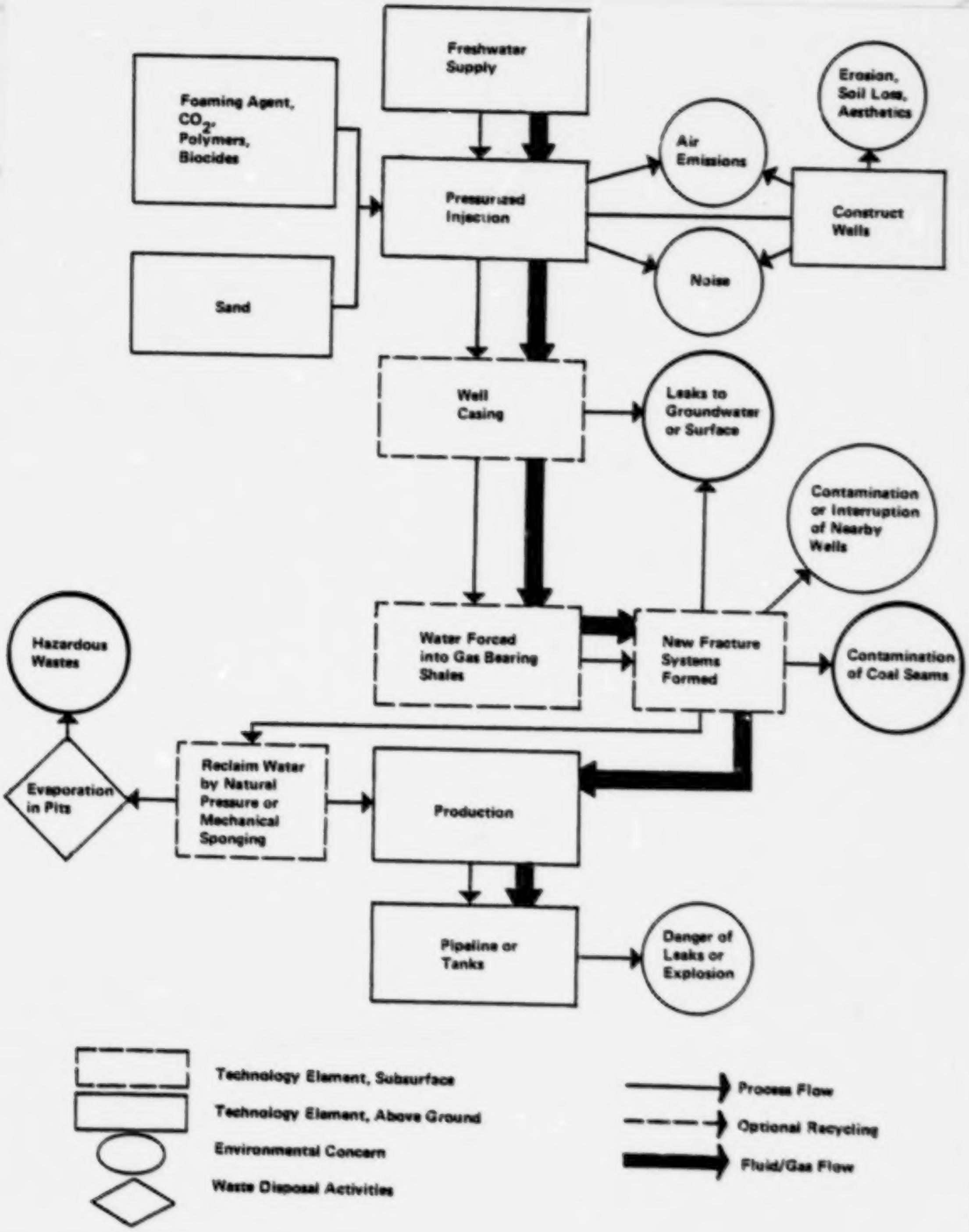
Freshwater Supply
Foaming Agent, CO2, Polymers, Biocides
Erosion, Soil Loss, Aesthetics
Air Emissions
Pressurized Injection
Construct Wells
Noise
Sand
Well Casing
Leaks to Groundwater or Surface
Contamination or Interruption of Nearby Wells
Hazardous Wastes
Water Forced into Gas Bearing Shales
New Fracture Systems Formed
Contamination of Coal Seams
Evaporation in Pits
Reclaim Water by Natural Pressure or Mechanical Sponging
Production
Pipeline or Tanks
Danger of Leaks or Explosion
Technology Element, Subsurface
Technology Element, Above Ground
Environmental Concern
Waste Disposal Activities
Process Flow
Optional Recycling
Fluid/Gas Flow

Figure 23. Process flow sheet, advanced hydraulic fracturing.

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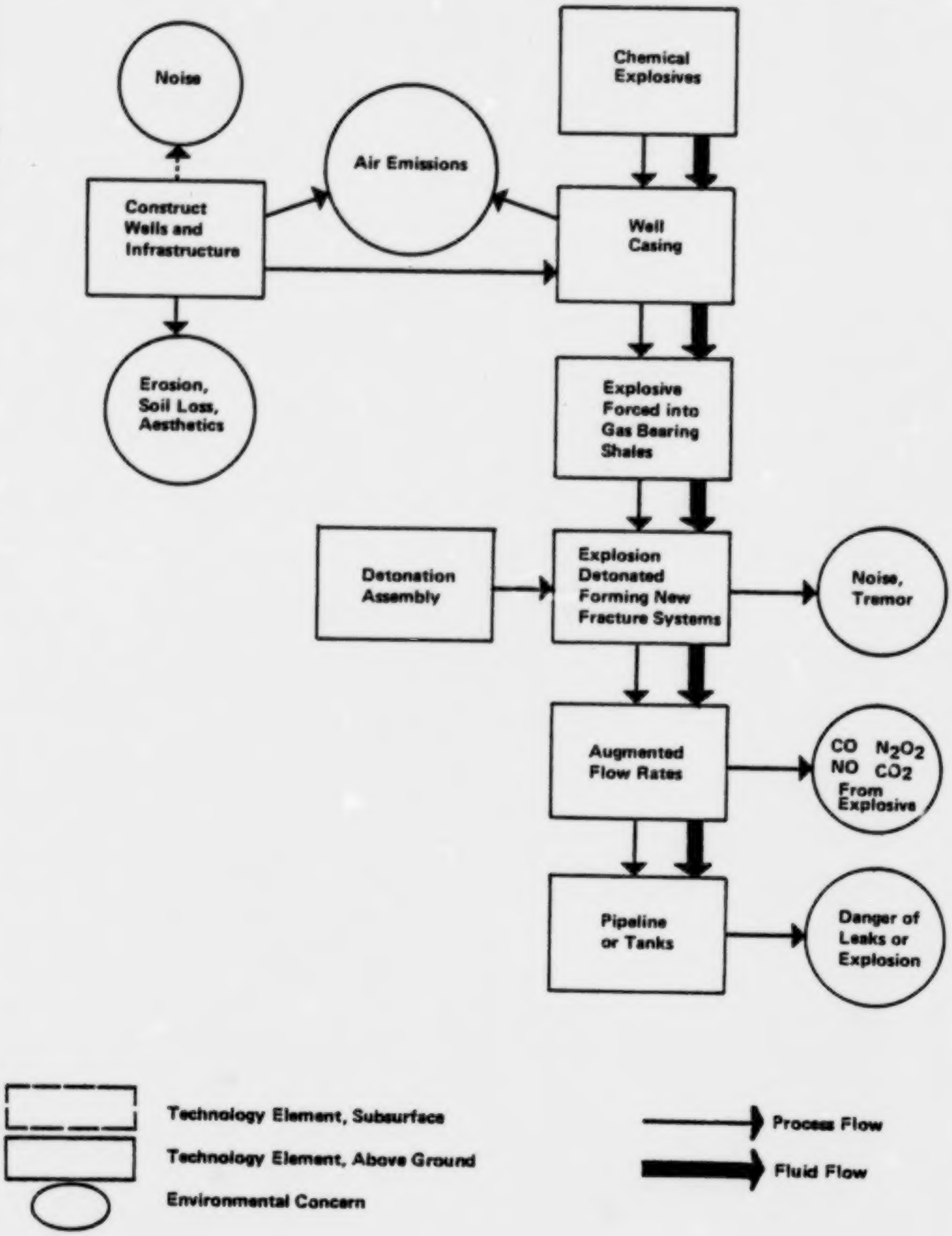
Noise
Chemical Explosives
Air Emissions
Construct Wells and Infrastructure
Well Casing
Erosion, Soil Loss, Aesthetics
Explosive Forced into Gas Bearing Shales
Detonation Assembly
Explosion Detonated Forming New Fracture Systems
Noise, Tremor
Augmented Flow Rates
CO N2O2 NO CO2 From Explosive
Pipeline or Tanks
Danger of Leaks or Explosion
Technology Element, Subsurface
Technology Element, Above Ground
Environmental Concern
Process Flow
Fluid Flow

Figure 24. Process flow sheet, chemical explosive fracturing.

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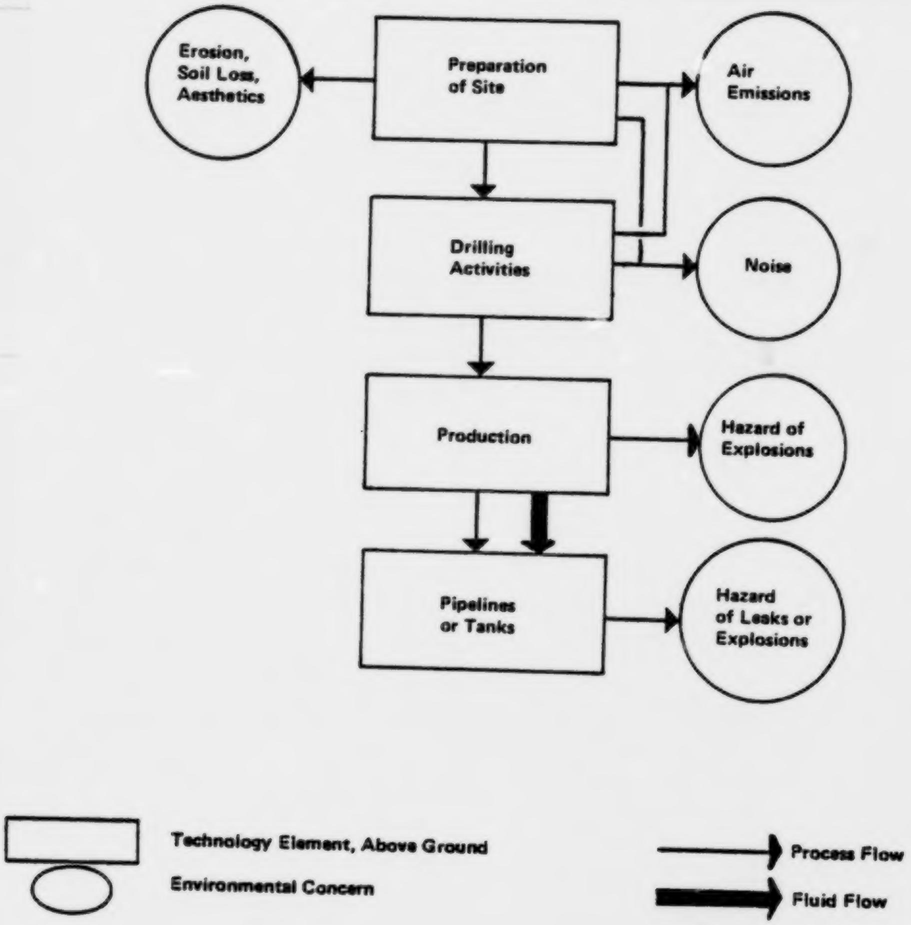
Erosion, Soil Loss, Aesthetics
Preparation of Site
Air Emissions
Drilling Activities
Noise
Production
Hazard of Explosions
Pipelines or Tanks
Hazard of Leaks or Explosions
Technology Element, Above Ground
Environmental Concern
Process Flow
Fluid Flow

Figure 25. Process/pollutant flow sheet, directional drilling.

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waterflooding, micellar-polymer flooding, alkaline flooding, and CO_2 miscible flooding. These process flows represent only a first step in the environmental evaluation process, since the presently available data, which are presented in this section, are not sufficient to complete the flow sheet with numbers representing magnitudes of pollutants.

To use these process flow sheets, identify the pollutant of interest from the figure and then refer to the relevant subsection of this section which discusses that pollutant medium.

Environmental Impacts of Secondary Oil Recovery

Previous work done on secondary recovery processes was reviewed to make use of work on a related process. Unfortunately, studies done on the environmental effects of secondary recovery operations are sparse. The studies that have been prepared are concerned primarily with the environmental impacts of the large quantities of brine produced along with the oil. The brine disposal problem is common to primary and tertiary recovery as well as secondary. Since the mechanisms by which fresh water can be contaminated are basically the same for both secondary and tertiary processes, the secondary oil recovery assessments that do exist are of interest to tertiary oil recovery assessment as well. The Interstate Oil Compact Commission and three Federal agencies - the EPA, the Department of Energy, and the United States Geological Survey - have been involved in the brine disposal question associated with oil and gas recovery processes in general and have come to contradictory conclusions.

Federal Studies--

The EPA has done some work on the subject in conjunction with the Underground Injection Regulations of the Safe Drinking Water Act. The Draft Environmental Impact Statement of the State Underground Injection Control Program prepared by the Office of Water Supply contains only a cursory sketch of the overall brine production and disposal subject. Energy Resources Company recently prepared a report for the DOE on "Impact of the Safe Drinking Water Act on Energy Development." These reports suggest possible problems but are limited in their analysis by lack of data.

The Interstate Oil Compact Commission has summarized the reported amounts of produced oilfield waters disposal during 1963 for each state, both for waterflooding purposes (secondary recovery) and for disposal only. Table 14 gives a list of common impurities found in oilfield brines, taken from a study of brine disposal practices (G.W. Reid et al., 1974).

EPA-287 (Cin.)
(4-76)

TABLE 14. MEDIAN CONCENTRATION OF TRACE METALS IN PRODUCED WATER[a,b]

	Number of Samples	Total Solids (Median) (mg/1)	Co	Cr	Cu	K	Li	Mg
Illinois Basin	22	98	ND	2p	10p	300	15	6,000
Louisiana and Texas Gulf Coast	79	69	ND	<1p	<25p	300	ND	250
East Texas	88	66	ND[c]	ND	<1	<50	ND	250
North Texas	24	222	ND	<1p	150p	300	ND	5,000
West Texas and New Mexico	148	111	ND	2p	1p	350	15	1,000
Permian only	74	143	ND	2p	20	400	10	1,000
Pennsylvania only	34	115	ND	3p	<1p	300	10	1,000
Silurian-Devonian only	15	55	ND	2p	4p	300	10	400
Ordovician-Cambrian only	21	67	ND	<2p	4p	400	15	800
Anadarko Basin[d]	118	137	ND	10p	10p	250	10	1,550
Williston Basin, post-Paleozoic	25	59	<5P	<2p	25p	300	ND	250
Williston Basin, Paleozoic	55	173	ND	3p	3p	800	35	600
Powder River Basin	22	5	<5p	<2p	<25p	300	ND	40
Other Wyoming	28	5	ND	ND	ND	300	ND	100
Colorado	18	5	<5p	ND	<25p	300	ND	30
California	116	18	ND	5p	5p	45	ND	90
Seawater	-	35	0.27p	0.04 0.07p	1p 15p	380	0.1	1,272
Estimated Detection Limit	-	-	1p	1p	1p	50	2	10

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EPA-287 (Cin.)
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TABLE 14 (CONT.)

	Mn	Ni	Sn	Sr	Ti	V	Zr
Illinois Basin	175p	ND	<1p	300	<10p	ND	<10p
Louisiana and Texas Gulf Coast	3.5	<1p	<1p	85	<10p	ND	<10p
East Texas	3.3	<1p	3p	350	ND^{2}	ND^{2}	ND
North Texas	45	15p	12p	450	7p	ND	<10p
West Texas and New Mexico	1.8	<1p	<1p	200	<10p	ND	ND
Permian only	1.7	<1p	<1p	90	<10p	<1p	ND
Pennsylvanian only	2.8	<1p	<1p	300	<10p	<1p	ND
Silurian-Devonian only	300p	<1p	1p	90	<10p	ND	ND
Ordovician-Cambrian only	400p	<1p	1p	250	<10p	ND	ND
Anadarko Basin^{3}	5.6	6p	2P	300	<10p	<1p	<10p
Williston Basin, post-Paleozoic	300p	<3p	<1p	100	ND	<1p	ND
Williston Basin, Paleozoic	660p	ND	<1p	95	<10p	<1p	ND
Powder River Basin	450p	<3p	<1p	25	<10p	<1p	<10p
Other Wyoming	300p	ND	<1p	20	<10p	<1p	ND
Colorado	300p	<3p	<10p	20	<10p	<1p	<10p
California	950p	10p	2.5p	10	<10p	<1p	ND
Seawater	1p-10p	5.4p	3p	13	Present	0.3p	ND
Estimated Detection Limit	1p	1p	1p	16	10p	1p	10p

[a] Taken from Rittenhouse, Fulton, Grabowski, and Bernard.

[b] ND = below detection limits; p = concentration in parts per billion, otherwise parts per million;

[c] No data; less sensitive methods of detection used.

[d] Includes Oklahoma Platform and Ardmore Basin.

EPA-287 (Cin.)
(4-76)

The concentrations of impurities and the amounts of the toxic heavy metals that account for a significant part of the potential harmful effects of oilfield brines are important factors unaccounted for in the study by Reid et al., 1974. Another study shows the potential for harmful effects of reinjected brines entering formations other than those from which they were originally derived (Irvin and Morton, 1969). This study also summarizes the results of a 1974 survey by the Interstate Oil Compact Commission, "in which it was found that 22 of the oil-producing states reported having some groundwater contamination problems."

A more detailed account of the brine disposal problem is to be found in the EPA Report to Congress (U.S. EPA, 1977), prepared by the Office of Water Supply and the Office of Solid Waste Management Programs. It was found that in the 24 states that were studied in this report, almost 24 million barrels of brine were produced daily. The report also found that the "disposal of brine from oil and gas production activities has been a major cause of groundwater contamination in areas of intense petroleum exploration and development." There are two major factors involved in the oilfield related groundwater contaminations cited in this report. The first is brine disposal in evaporation pits that were unlined (today most states require impervious liners) and could leak salts and minerals into shallow freshwater zones. Many have been abandoned in the past decade after it was discovered that these pits were better described as leaching pits than evaporation pits, thus making it impossible to estimate the extent to which these pits contributed to the widespread contamination of near-surface waters.

In most states, the produced brines from oilfields are now reinjected back into old producing zones, brine injection wells for waterflooding or into a deeper saline aquifer solely for the purpose of disposal. The study found shortcomings in these methods because many of the wells used for reinjection are old or poorly designed for that purpose and they may induce the introduction of salt water into fresh water formations through ruptured or corroded casings (U.S. EPA, 1977c).

The study also points out that although enactment of state oil and gas laws related to our groundwater resources has demonstrated a recognized need for environmentally acceptable waste brine disposal, most legislation still seems to be concerned primarily with the economics of petroleum production. This is also the case for tertiary oil recovery considerations.

A number of specific instances of water supply contamination from brines have been recorded. The Interstate Oil Compact Commission recently (July 1978) released a report entitled "Impact of oil and gas production on salinity in major fresh water aquifers," which cited specific contaminant events. A principal instance is the Vamoosa aquifer which underlies large regions of Oklahoma. The USGS (D'Logosz and McClafin, 1978) has found that "both surface and ground waters have been degraded locally by sodium chloride brines." The USGS concludes that the most probable source of the brines which have polluted the aquifer is the extensive oil operations that have been carried out for decades in the region.

Surprisingly, there is little detailed information available on the composition of oilfield brines. Some data can be found in Collins (1975), and additional data are given in a paper by Rittenhouse et al. (1969). These sources are largely concerned with onshore oil production.

There is also a small body of work concerned with the impacts of brine disposal in offshore waters. The EPA Kerr Environmental Research Laboratory in Ada, Oklahoma has performed analyses of offshore wastewaters from 25 facilities. Substances measured included cyanide, chloride, sulfate, cadmium, and mercury (U.S. EPA, 1975e). Similar data were developed by the Western Oil and Gas Association and the Water Quality Board, State of California, and by the Offshore Operators Committee. Energy Resources Co. conducted a study of the impacts of brine discharge into coastal waters in which the above-cited data and numerical dispersion modeling were used to estimate concentrations of discharged pollutants (Shore et al., 1977). The report concluded that there was some cause for concern because of the presence of toxic trace metals and of soluble aromatic hydrocarbons in the oilfield brines.

A DOE paper reviewing the principles and logistics of oilfield brine reinjection (Donaldson, 1977) states that the injection of wastes (brines and petrochemicals) into deep formations is the most economical disposal method and suggests the use of this type of disposal but acknowledges that much more research needs to be done on the eventual fate of injected fluids. The paper includes some lists of inorganic chemicals currently being disposed of in deep injection wells. Also illustrated are the design and the various completion systems of waste disposal wells; see Figures 26 and 27.

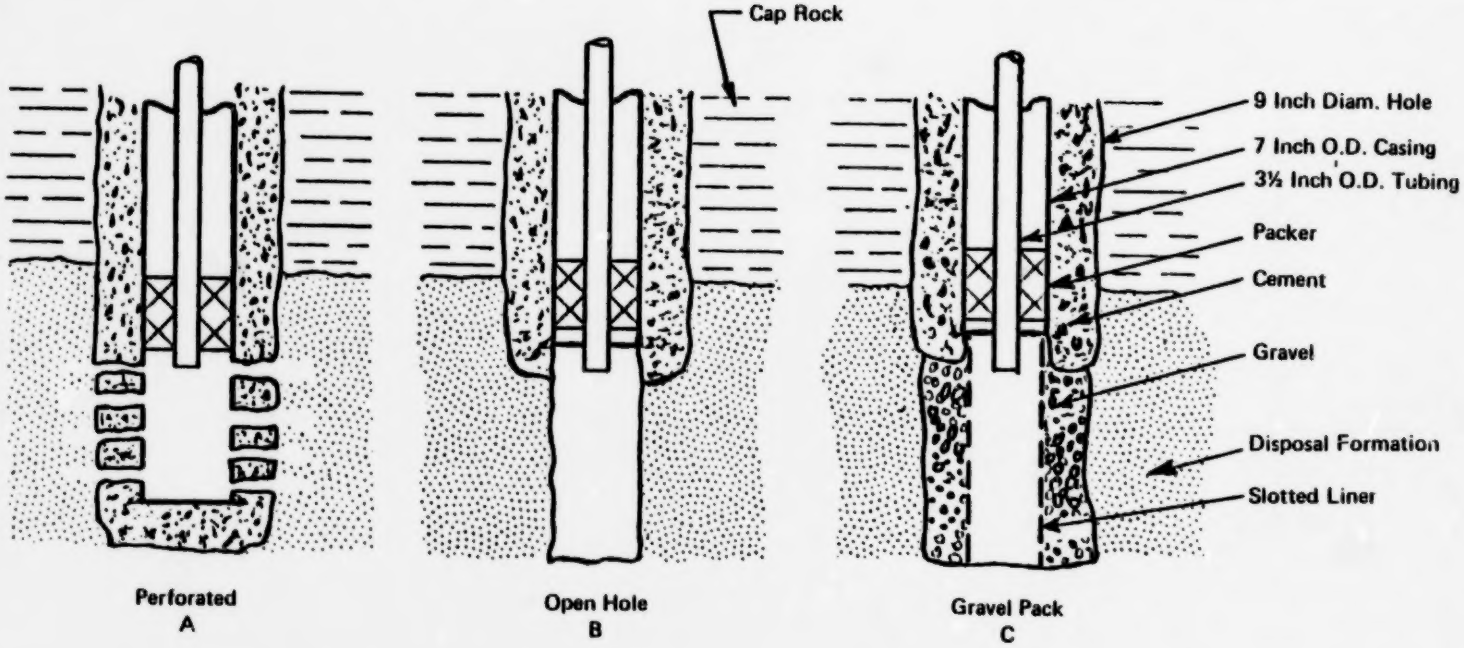
Cap Rock
9 Inch Diam. Hole
7 Inch O.D. Casing
3½ Inch O.D. Tubing
Packer
Cement
Gravel
Disposal Formation
Slotted Liner
Perforated
A
Open Hole
B
Gravel Pack
C

Figure 26. Disposal-well completion methods. (Donaldson, 1977).

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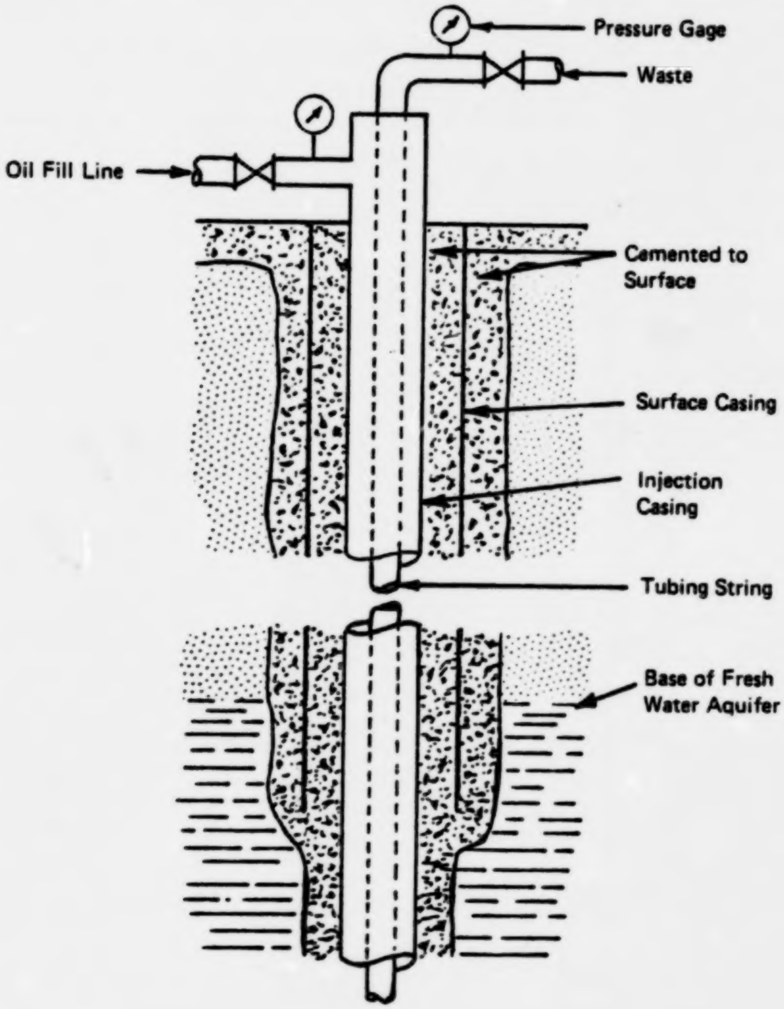
Pressure Gage
Waste
Oil Fill Line
Cemented to Surface
Surface Casing
Injection Casing
Tubing String
Base of Fresh Water Aquifer

Figure 27. Waste-disposal well. (Donaldson, 1977).

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EPA-287 (Cin.)
(4-76)

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Another pollutant concern, associated with all types of oil recovery developments and the composition of the drilling muds and fluids used, includes bactericides, emulsifiers, lubricants, flocculants, surface active agents, foaming agents, thinners or dispersants, calcium removers, and corrosion inhibitors. The chemical compositions or families of most of the substances thus used have been listed by World Oil (1977) and the API (1978b). Some of the listed substances may have very adverse affects on the environment; however, the amounts used are usually relatively small compared to flooding agents.

AIR QUALITY DEGRADATION

The two categories of air emissions from enhanced recovery operations are combustion products and escaping reservoir gases. This section presents impacts assessment methodology, summarizes available data regarding the various emissions, and discusses the control rationale.

Impacts Methodology

A general procedure for evaluating an enhanced recovery project, or for evaluating a regionalized group of projects, is presented in Figure 28. Impacts are dependent on a variety of site-specific factors, hence, this methodology is not suitable for a general technology-wide impacts analysis. Of particular concern are pollutants not included in current air regulations. This includes a variety of trace contaminants which may be generated in and mobilized from the reservoir by the temperatures generated in thermal recovery processes.

Analysis of Existing Data

Enhanced oil and gas recovery processes have a considerably greater potential for causing air quality degradation than do conventional (primary and secondary) recovery technologies. During conventional recovery, air quality impacts result principally from (1) the emissions associated with production and injection pumps, and (2) fugitive emissions from wellheads and handling and storage facilities. In addition to those produced by conventional operations, enhanced recovery technologies produce emissions from steam generators (boilers) in steam flood operations; fugitive emissions containing combustion products produced by in situ combustion to volatile organic fractions; emissions from the combustion engines of compressors used in CO_2 miscible floods and in situ combustion; and emissions resulting from on-site chemical preparation, injection, and separation from produced oil.

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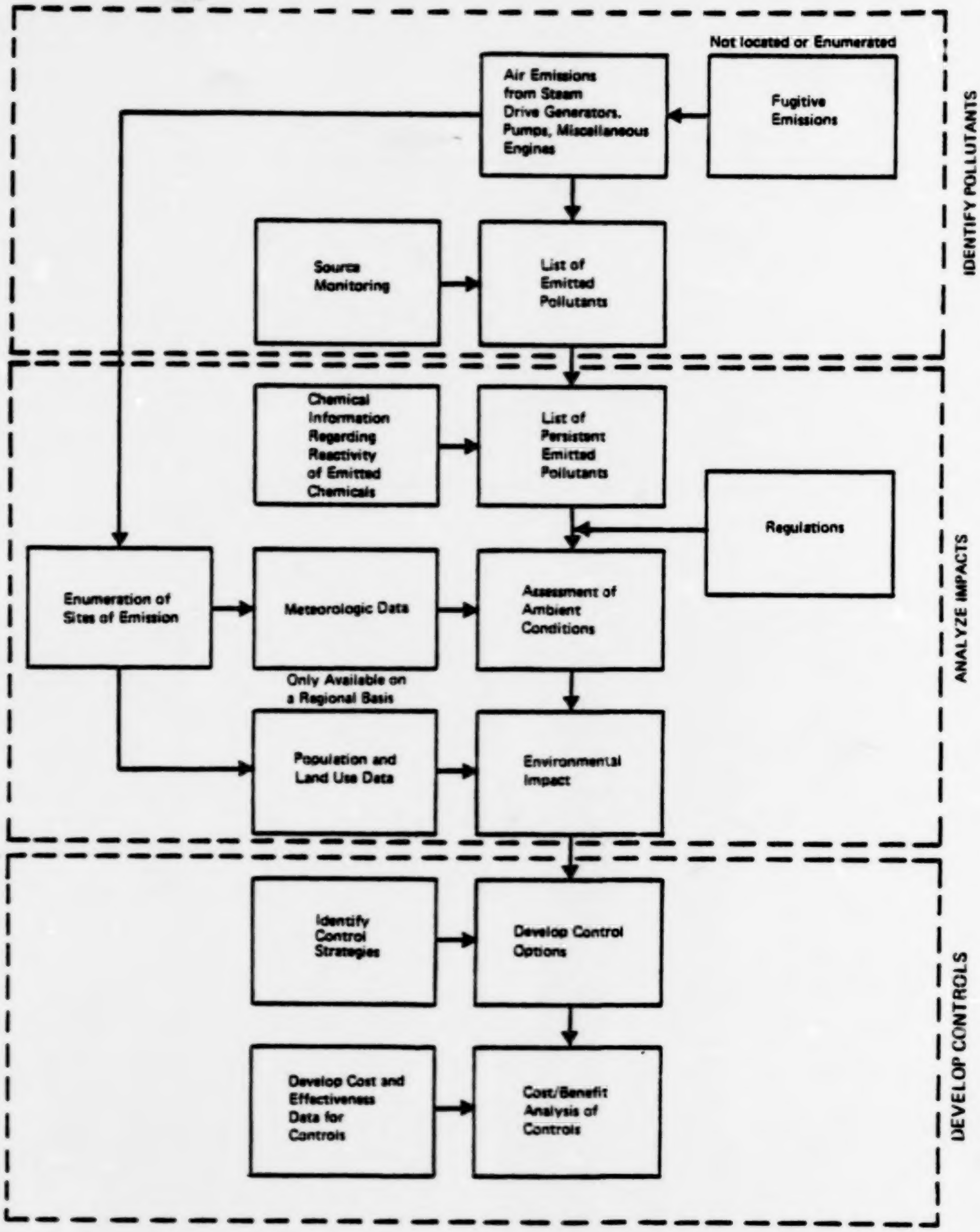
Not located or Enumerated
Air Emissions from Steam Drive Generators, Pumps, Miscellaneous Engines
Fugitive Emissions
Source Monitoring
List of Emitted Pollutants
IDENTIFY POLLUTANTS
Chemical Information Regarding Reactivity of Emitted Chemicals
List of Persistent Emitted Pollutants
Regulations
Enumeration of Sites of Emission
Meteorologic Data
Assessment of Ambient Conditions
Only Available on a Regional Basis
Population and Land Use Data
Environmental Impact
ANALYZE IMPACTS
Identify Control Strategies
Develop Control Options
Develop Cost and Effectiveness Data for Controls
Cost/Benefit Analysis of Controls
DEVELOP CONTROLS

Figure 28. Air Impacts Methodology.

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Table 15 identifies the major air pollutants associated with each technology and lists the estimated emission levels per barrel of produced oil. As the table indicates, the major air emissions produced in enhanced recovery operations are: sulfur oxides, nitrogen oxides, particulates, hydrocarbons and hydrocarbon fractions, hydrogen sulfide, carbon monoxide, carbon dioxide, and ozone. It is difficult to definitively rank these in terms of importance. Current concerns center on SO_x, NO_x, and fine particulates. Minor pollutants include a variety of volatilized organics and organics and metals adsorbed on particulates.

Most of these emissions are products or byproducts of the on-site combustion of high-sulfur crude oil for thermal recovery by the steam drive, steam soak, and in situ combustion technologies. The major emissions of the steam flood technology result from the powering of steam generators, while for in situ combustion, fugitive air emissions result from the burning of oil in the reservoir to reduce the viscosity of remaining oil. Emissions from on-site chemical preparation, especially the mixing of polymers, and from chemicals spills and leaks, are primarily of significance in terms of occupational safety, since they will generally be sporadic and limited in impact.

In this section the impacts of these various emissions are discussed in terms of their origins, ambient concentrations, major enhanced recovery sources, emission levels, health impacts, and applicable federal and California standards. Tables 16 through 18 summarize the existing data and identify information gaps. Generally, most of the troublesome emissions expected from enhanced recovery are attributable to steam flooding, steam soak, and in situ combustion.

Impacts

Sulfur Oxides (SO_x)--

Sulfur oxides are formed when sulfur in fuel combines with oxygen in a high-temperature environment. SO_x can also be produced by natural sources, that is, volcanic eruptions or subterranean heat sources; these sources have been estimated to emit 4.2×10^6 tons/yr of SO_x globally. However, the most significant contributions to ambient SO_x levels are from the combustion of sulfur-containing fossil fuels, which are estimated to produce 31.1×10^6 tons/yr of SO_x globally. The average annual ambient concentration of SO_x has been reported to be 19 $\mu g/m^3$ in the United States, 62.6 percent of which is attributed to stationary combustion sources (Laska, 1978).

TABLE 15. ATMOSPHERIC EMISSIONS FOR EACH EOR/EGR TECHNOLOGY[a]

EOR/EGR Technology	Major Emissions Associated with Technology	Average Emission per Barrel Produced Oil (lb)	Minor Pollutant	Significant Pollutants: Based on Data	Significant Pollutants: Engineering Estimates Based on Qualitative Data	Significant Pollutants: Insufficient Data
EOR Steam Flood[b]	Sulfur oxides (SO_x)	(1.81-2.42)		x		
	Nitrogen oxides (NO_x)	(0.63-0.84)		x		
	Particulates (P)	(0.17-0.23)		x		
	Hydrocarbons (HC)	(0.02-0.03)	x			
	Carbon monoxide (CO)	(0.04-0.06)	x			
EOR in situ combustion	Sulfur oxides (SO_x)	NA			x	
	Particulates (P)	NA			x	
	Hydrocarbons (HC)	30	x			
	Carbon monoxide (CO)	11		x		
	Carbon dioxide (CO_2)	50		x		
	Hydrogen sulfide (H_2S)			x		
EOR CO_2 flood	Sulfur oxides	NA				x
	Nitrogen oxides	NA				x
	Particulates	NA				x
	Hydrocarbons	NA				x
	Carbon monoxide	NA			x	
	Carbon dioxide	NA			x	
	Hydrogen sulfide	NA			x	
EOR micellar polymer flood	Sulfur oxides	NA				x
	Nitrogen oxides	NA				x
	Particulates	NA				x
	Hydrocarbons	NA			x	
	Carbon monoxide	NA				x
	Carbon dioxide	NA				x
	Hydrogen sulfide	NA				x
	Polymer	NA			x	
	Chemicals	NA			x	
For improved and alkaline water flooding	Sulfur oxides	NA				x
	Nitrogen oxides	NA				x
	Particulates	NA				x
	Hydrocarbons	NA			x	
	Carbon monoxide	NA				x
	Carbon dioxide	NA				x
	Hydrogen sulfide	NA				x
	Chemicals	NA				x
EGR advanced hydraulic fracture	Hydrocarbons	NA				x
	Hydrogen sulfide	NA				x
EGR chemical explosive fracture	Hydrocarbons	NA				x
	Hydrogen sulfide	NA				x
	Chemicals	NA				x
EGR directional drilling	Hydrocarbons	NA				x
	Hydrogen sulfide	NA				x

[a] ERCO estimates based on published and unpublished data.

[b] Assumes: 1 bbl oil burned per 3-5 bbl produced; generators operate 292 days per year.

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TABLE 16. SUMMARY OF IMPACTS OF EOR AIR EMISSIONS

Chemical	Health and Environmental Effects	EOR Process	Origin
Carbon monoxide	• At high concentrations, can produce blood COHb levels above 5 percent--physiologic stress on patients with heart disease	Especially steam flood, in situ combustion	Combustion product
Aliphatic and alicyclic hydrocarbons	• Promote formation of photochemical smog and thus contribute to eye irritation • No effects reported below 500 ppm	All; especially steam flood, in situ combustion	Combustion byproduct
Aromatic hydrocarbons	• Aromatic hydrocarbons are irritating to mucous membranes. Systematic injury can result from the inhalation • No effects reported below 25 ppm	All; especially steam flood, in situ combustion	Combustion byproduct
Nitrogen oxides (nitrogen dioxide)	• Can reduce visibility - absorbs light energy over the entire spectrum • Contributes to photochemical oxidants • Significantly correlated with increased respiratory disease at mean 24-hour concentrations between 117-205 $\mu g/m^3$ (0.062-0.109 ppm)	All; especially steam flood, in situ combustion	Combustion byproduct
Particulates	• Can cause injury to the surface of the respiratory system • Lowest particulate levels at which deleterious health effects have occurred are reported to be 100 $\mu g/m^3$ over a 2-year period (with SO_x pollution also present)	All; especially steam flood, in situ combustion	Combustion product

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EPA-287 (Cin.)
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TABLE 16 (CONT.)

Chemical	Health and Environmental Effects	EOR Process	Origin
Sulfur oxides (sulfur dioxide)	• Causes irritation of the respiratory system (may be temporary or permanent) • Can produce bronchioconstriction increases in guineau-pig pulmonary flow. Increases detectable at 0.16 ppm (460 $\mu g/m^3$) • Can react with rain to produce sulfuric acid • Corrodes various metals, electrical equipment (overhead power lines), limestone, marble, roofing slate, cotton, rayon and nylon • Affects pulmonary function at 1.6 ppm over 10 minutes • Discomfort experienced at 5 ppm • Severe distress experienced at 5-10 ppm	All; especially steam flood, in situ combustion	Combustion product
Hydrogen sulfide	• Affects central nervous system at 0.1 ppm over 1 hour • Affects pulmonary function at 250-260 ppm for prolonged exposure • Lethal at 400-700 ppm 1/2-1 hr	All; especially CO_2-flood, in situ combustion	Interaction of hydrogen and sulfur in a reduction environment
Photochemical oxidants	• Can affect respiratory functions, depending on concentration, time of exposure, degree of activity, and state of health	All; especially steam flood, in situ combustion	Produced by atmospheric interactions among organic pollutants, NO_x, O^2, and sunlight

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 17. TYPICAL GENERATOR EMISSION RATE SUMMARY[a]

Approximate Rate Output (10^6 Btu/hr)	Typical Daily Fuel Consumption (bbl/day)	Typical Yearly Operating Schedule (days)	Emissions (lb/bbl fuel burned)					Emissions (lb/bbl fuel recovered)					Emissions (tons/yr)				
			SO_2[b]	NO_2	P	HC	CO	SO_2[b]	NO_2	P^1	HC	CO	SO_2[b]	NO_2	P	HC	CO
5	10	292	7.3	2.5	0.7	0.1	0.2	1.81-2.42	0.63-0.84	0.17-0.23	0.02-0.03	0.04-0.06	26.5	9.2	2.6	0.4	0.7
10	50	292	7.3	2.5	0.7	0.1	0.2	1.81-2.42	0.63-0.84	0.17-0.23	0.02-0.03	0.04-0.06	53.0	18.4	5.1	0.7	1.4
20	90	292	7.3	2.5	0.7	0.1	0.2	1.81-2.42	0.63-0.84	0.17-0.23	0.02-0.03	0.04-0.06	95.4	33.1	9.2	1.3	2.6
50	210	292	7.3	2.5	0.7	0.1	0.2	1.81-2.42	0.63-0.84	0.17-10.23	0.02-0.03	0.04-0.06	222.6	77.3	21.5	3.1	6.1

[a] Draft Environmental Impact Report for the Proposed Arroyo Grande Thermal Project, Teal Petroleum, Office of Environmental Quality, County of San Luis Obispo, California, March 1978, p. D-4 #925; Sheridan, R.S., Air Quality Impact of Proposed Oil-Fired Equipment in the Western Kern Co. Oil Fields through Year End 1978. Vol. 1, SAI, La Jolla, April 1977, p. 29.

[b] Assuming use of fuel containing 1.1 percent sulfur by weight.

[c] Assume 1/4-1/3 of fuel recovered is used in recovery process.

EPA-287 (Cin.)
(4-76)

TABLE 18. AVERAGE EMISSIONS OF GASEOUS COMPOUNDS FROM IN SITU COMBUSTIONS[a,b]

Compound	Emissions (standard cubic feet per barrel of oil produced)
Carbon dioxide	435
Carbon monoxide	160
Nitrogen	4,220[d]
Oxygen	185
Hydrocarbons	150

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[a] Braxton, C., C. Muller, J. Post, R. Stephens, and J. White. Potential Environmental Consequences of Tertiary Oil Recovery. ERCO #140 for EPA. 1976.

[b] Assumes all sulfur compounds remain in solution with produced water. However, emissions of SO_x may occur in the late phases of a fire flood.

[c] Based on a survey of the gas streams of 31 fire floods (average value).

[d] Formation of NO_x compounds is not favored at the typical burning temperatures in a fire flood of 700° F to 1,200° F. Most of the emissions would probably be nitrogen.

In EOR operations, sulfur oxides are produced by thermal, micellar-polymer, and caustic waterflooding technologies in the powering of generators, compressors, and pumps, and in burning oil for in situ combustion recovery. Steam drive, and to a lesser extent, steam soak, require a high-energy input; burning an average 25 to 30 percent of their product for recovery. Steam generators are the major source of sulfur oxide emissions and typically emit approximately 7.3 lb of sulfur dioxide per barrel of fuel burned (assuming 1.1 percent sulfur by weight). This can reach levels of 21.5 tons of sulfur dioxide per year per generator if one assumes constant operation of a generator with a rated output of 50 x 10^6 Btu/hr (Sheridan, 1977). Other above-ground energy users, that is, compressors and pumps, have such small fuel requirements that their emissions are negligible. No monitoring has been performed for in situ combustion sites, but related work in pyrolysis of oil shale suggests that the fugitive emissions from in situ processes are significant (Braxton, 1976).

Sulfur oxides affect general public health primarily by acting as respiratory irritants. Sulfur dioxide is usually the dominant component of SO_x and is the common standard for measuring airborne sulfur, although sulfuric acid, produced when sulfur dioxide combines with water ("acid rain"), and particulate sulfates have greater irritant potency at a given concentration than does sulfur dioxide alone.

The heart and lungs are the major target organs for SO_x. The presence of SO_x increases bronchioconstriction,[36] hence aggravating asthma and emphysema and decreasing lung ventilation (Laska, 1978). Studies of episodes occurring in London indicated that there was a significant rise in the daily death rate when the street level concentration of SO_2 rose abruptly to approximately 0.25 ppm. Likewise, increased frequency and severity of respiratory diseases in school children in Great Britain occurred when long-term pollution levels exceeded averages of approximately 0.046 ppm sulfur dioxide and 100 µg/m^3 for smoke (particulates) U.S. EPA, 1973). It has been shown by case studies of the combined effects of sulfur oxides and particulates over 24-hour periods that 0.037-0.092 ppm SO_2 combined with 185 µg particulates caused an increased frequency of respiratory symptoms and lung disease, and that 0.04 ppm SO_2 combined with 160 µg/m^3 particulates caused increased mortality in exposed populations from bronchitis and lung cancer (U.S. EPA, 1973).

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[36] A condition in which oxygen intake to the lungs is reduced.

The Threshold Limit Value (TLV)[37] for SO_2 is 5.0 ppm. Federal Primary Ambient Air Standards[38] for SO_2 are: 365 μg/m^3 (0.14 ppm) - 24 hour standard; 80 μg/m^3 (0.03 ppm) - annual standard. The secondary standard[39] is 1,300 μg/m^3 (0.05 ppm) (40 CFR 50). California standards set maximum emission levels at 1,300 μg/m^3 (0.5 ppm) for one hour or 130 μg/m^3 (0.05 ppm) averaged over a 24-hour period (State of California, 1978). Because the California standards are often more strict than the federal standards, and because almost all U.S. steam flood operations are currently taking place in California, consideration of the state air pollution standard is important in an analysis of air emission impacts.

Nitrogen Oxides (NO_x)--

Oxides of nitrogen (NO_x) are produced in combustion processes both from thermal fixation of atmospheric nitrogen and from conversion of chemically-bound nitrogen contained in the fuel being burned. The rate of NO_x formation primarily depends on temperature and oxygen concentration in the combustion zone. Fuel type, as the source of chemically-bound nitrogen, is also important. Both nitric oxide (NO) and nitrogen dioxide (NO_2) are emitted by natural sources[40] in greater amounts than by man-made sources on a global scale; natural sources producing about 500 x 10^6 tons of NO per year, while man-made sources have been estimated to emit 50 x 10^6 tons of NO_x (EPRI, 1978). Ambient nonurban concentrations have been estimated to be 8 μg/m^3 (0.004 ppm) for NO_2 and 2 μg/m^3 (0.002 ppm) for NO (U.S. EPA, 1971).

Generators used in steam drive thermal processes are he most significant source of nitrogen oxide emissions followed by gases released from in situ combustion and steam flooding. Emissions of NO_2 from typical generators is approximately 2.5 pounds per barrel of fuel (Sheridan et al., 1977), or about 0.8 pounds per barrel produced.

NO is converted to NO_2 by photochemical oxidation, and both are important components of the photochemical reactions which lead to the formation of smog. However, NO_2 is approximately four times as toxic as NO. NO_2 exerts its primary toxic effect on the lungs and at high levels can

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[37] Or, the concentration of a substance to which a worker can be exposed 8 hours per day or 40 hours per week without significant health effects or discomfort.

[38] Primary standard: to protect public health.

[39] Secondary standard: to protect public welfare.

[40] Natural sources, including geologic processes, respiration, natural fines, and organic decay.

EPA-287 (Cin.) (4-76)

cause pulmonary edema and death. At low levels adverse health effects are evidenced as bronchitis and respiratory ailments including emphysema, polycythemia, leucocytosis, and sensitivity to infection (Mitre, 1976).

A high incidence of acute bronchitis among infants and school children has been observed when the mean 24-hour NO_2 concentration over a 6-month period was 118-156 $\mu g/m^3$ (0.63-0.83 ppm). Likewise, high incidence of acute respiratory disease was observed when the mean 24-hour NO_2 concentration over a 6-month period was 117-205 $\mu g/m^3$ (0.062-0.109 ppm) and the mean suspended nitrate level was 3.8 $\mu g/m^3$ or higher. Concentrations higher than 100 ppm are lethal to most species, death being caused by pulmonary edema (U.S. EPA, 1971).

The TLV for NO is 650 $\mu g/m^3$ (25 ppm), for NO_2 is 130 $\mu g/m^3$ (5.0 ppm) and for HNO_3 is 74 $\mu g/m^3$ (2.1 ppm). The Federal Primary Ambient Air Standard is 100 $\mu g/m^3$ (0.05 ppm) as an annual arithmetic mean; however, this standard does not stipulate emission levels over shorter periods (40 CFR 50). California standards (1978) for nitrogen dioxide are the same as the Federal standards for annual mean emissions but additionally limit emission levels to 65 $\mu g/m^3$ (0.25 ppm) over a 1-hour period.

Particulates--

Particulate matter may be airborne for a variety of reasons, but its primary source is probably pickup and dispersal by wind and dust storms. However, the combustion process introduces an estimated 8 x 10^6 tons/yr of particulates into the atmosphere as ash and organic material carried with hot escaping gases (Laska, 1978). The ambient mean annual concentration of particulates was estimated to be 60 $\mu g/m^3$ in 1975, but may have decreased since that time (Laska, 1978).

Combustion of fuel in thermal oil recovery will be the primary source of particulates in enhanced operations, although dust from construction and the mixing of chemicals can also have localized health impacts. Particulate emissions from steam generators are estimated at 0.7 pounds per barrel of fuel burned (Sheridan et al., 1977).

Particulate emissions, especially those in the size range of 0.5 to 5.0 μ in diameter, are responsible for both temporary and permanent health related problems related to injury to the surfaces of the respiratory system. Chronic symptoms due to lung scarring include: difficult breathing, chest pain, cough, decreased vital capacity, and heart disease (Mitre, 1976). The lowest particulate levels at which health effects appear to have occurred are 100 $\mu g/m^3$, but small particles and the presence of sulfur oxides may cause adverse health effects at lower concentrations. Increased mortality may be associated with 2-year geometric means at 8-100 $\mu g/m^3$, but presence of sulfur oxides makes the specific role of particulates in health degradation difficult to determine (NAPCA, 1969).

The TLV for total particulates is 10 $\mu g/m^3$. The Primary National Ambient Air Quality Standard for Suspended Particulates is 75 $\mu g/m^3$ (annual), and 260 $\mu g/m^3$ (24 hr). The secondary standard is 60 $\mu g/m^3$ (annual) and 150 $\mu g/m^3$ (24 hr) (40 CFR 50). California Standards for particulates (1978) give a maximum 24-hr level of 60 $\mu g/m^3$ annual mean and 100 $\mu g/m^3$ for a single 24-hr sample. Thus, for particulates, the California state standard is much stricter than the federal standard.

Hydrocarbons--

Hydrocarbons and hydrocarbon fractions are volatile and approximately 50 percent of the estimated annual mean ambient level is thought to originate from natural sources such as the evaporation from fossil reservoirs, that is, tar sands, and natural gas. However, 37 x 10^6 tons/yr of hydrocarbons are estimated to be produced in conjunction with combustion processes in the United States. These are usually the result of incomplete combustion in internal commbustion engines. Of the total estimated annual mean 67.6 x 10^6 tons (Laska, 1978) of hydrocarbons produced per year, 0.5 percent or 0.4 x 10^6 are attributed to stationary combustion sources. Ambient nonurban levels are approximately 0.7 to 1.0 $\mu g/m^3$ (1 to 1.5 ppm) for methane and less than 0.1 ppm for other hydrocarbons (NAPCA, 1970b).

Hydrocarbons are emitted from virtually all oil recovery processes, but emission levels will be highest for thermal processes, especially steam soak and steam drive that involve both combustion emissions and the volatilization (and some fugitive release) of the product. In situ combustion operations emit hydrocarbons primarily in the venting of gases at production wells or as fugitive emissions. A typical steam generator operation will produce 0.1 lb hydrocarbons/bbl oil burned (Sheridan et al., 1977), while in situ combustion emissions may contain on the order of 30 lb hydrocarbons/bbl oil produced (Braxton et al., 1976).

Hydrocarbons have their greatest impact in entering into and promoting the formation of photochemical smog, thus causing irritation to the eyes and sensitive membranes of the respiratory tract. Examination of air quality data has shown that a concentration of 0.3 ppm of typical composition non-methane

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EPA-287 (Cin.)
(4-76)

light hydrocarbon mixture can be expected to produce a maximum hourly average oxidant concentration of 0.1 ppm (NAPCA, 1970b). Products of photochemical reactions identified as eye irritants include formaldehyde, acerolein, peroxyacyl nitrates, peroxybenzoyl nitrate, ketones, and other aldehydes. Additionally, hydrocarbons combined with nitrogen oxides act as precursors for eye irritants as do the alkylbenzenes and olefins. The criteria for hydrocarbon emissions are thus founded almost entirely on their role as precursors of compounds formed in the atmospheric photochemical system rather than on the hydrocarbons themselves (NAPCA, 1970b).

The aliphatic and alicyclic hydrocarbons are generally biochemically inert, though not biologically inert, and are only reactive at concentrations 10^2 to 10^3 higher than ambient levels; no effects having been reported below 500 ppm. Aromatic hydrocarbons, on the other hand, are biochemically and biologically active. Their vapors are irritating to mucous membranes but no effects have been reported at levels below 25 ppm (NAPCA, 1970b).

Federal Ambient Standards (1978) for hydrocarbons set a maximum 3-hr concentration limit of 160 $\mu g/m^3$ (0.24 ppm) (40 CFR 50). This limit has been devised primarily because of the important role hydrocarbons play in the formation of photochemical oxidants. No California standards have yet been promulgated.

Hydrogen Sulfide (H_2S)--

Hydrogen sulfide is a reduced form of sulfur, often produced when sulfur is heated in the absence of oxygen. Its production is often associated with geothermal sources, for example, hot springs, and it is emitted in significant quantities both as one of the production gases in carbon dioxide flooding and in situ combustion.

Data on emissions have been collected by Chanslor-Western Oil in California for their fire-flood in Kern County but this information is not currently available. The amounts of H_2S emitted in conjunction with CO_2 flooding have not been measured.

H_2S is highly toxic and is principally absorbed into the bloodstream through the lungs. The portion of the gas that first comes into contact with moist tissues such as the eyes and the respiratory mucosa combines with alkali in the tissues to form sodium sulfide, a caustic irritant responsible for the irritative effects of H_2S. Systematic effects result from absorption of H_2S into the blood stream at a rate faster than it can be detoxified, and the consequent perfusion and paralysis of the central nervous system by unoxidized H_2S. At high concentrations this can lead to asphyxiation (IIEQ, 1974). Exposure at levels as low as 120 $\mu g/m^3$ may result in fatigue, nausea, vomiting, diarrhea, pulmonary edema, eye irritation, and dizziness. Chronic exposure can cause kidney, liver, and/or brain damage. Respiratory tract irritation occurs at H_2S concentrations of 70 mg/m^3 (IIEQ, 1974).

The TLV for H_2S is 26 $\mu g/m^3$ (10 ppm) (Laska, 1978) for µkin and California ambient standards (1978) set a maximum 26 g/m^3 (0.03 ppm) over a 1-hour period. Federal ambient standards have not yet been determined.

Carbon Monoxide (CO)--

One of the major sources of atmospheric carbon monoxide is in the incomplete combustion of organic material, with automobiles accounting for the major emissions (111.5×10^6 tons/yr) and stationary combustion sources accounting for an estimated 1.1×10^6 tons/year in the United States (Laska, 1978). The 1970 background concentration of CO is varied from 29 to 11,500 $\mu g/m^3$ (0.025 to 1.00 ppm) (NAPCA, 1970a) depending upon the distribution of combustion sources.

Thermal processes are the major sources of CO_2 associated with enhanced recovery. The generators used in steam flooding and fossil-fuel-fired equipment and the combustion of fuel in situ produce CO as carbon combines with oxygen during the combustion process. Steam generators are reported to produce CO at an average rate of 0.025 lb/bbl fuel burned. Emission levels at the source of gas streams released from in situ combustion operations are estimated to be 71 lb/bbl of oil produced.

Carbon monoxide is absorbed by lung tissue and reacts with hemoglobin in the blood, displacing the oxygen that hemoglobin reacts with in a normal low-CO environment and that hemoglobin would have carried through the blood to supply to body tissues. Long-term exposure to high-CO concentrations lowers oxygen availability for metabolism and may cause compensatory structural changes in heart and brain cells. Symptoms of exposure include: headache, dizziness, nausea, vomiting, systemic pain and fatigue (Laska, 1978). The lowest concentration at which symptoms occur is approximately 58 mg/m^3 (50 ppm) at continuous exposure for six weeks (NAPCA, 1970a).

The TLV for CO is 130 $\mu g/m^3$ (50 ppm). The National Primary Ambient Air Standard is 10,000 $\mu g/m^3$ (9 ppm) for 8-hour samples averaged over a year; 40,000 $\mu g/m^3$ (35 ppm) for 1-hour samples averaged over a 24-hour period, neither of which is to be exceeded more than once annually (40 CFR 50). California standards for CO (1978) specify that ambient levels must not exceed 2.6 mg/m^3 (10 ppm) over any 12-hour period and not exceed 10.4 mg/m^3 (40 ppm) for any 1-hour period.

Carbon Dioxide (CO_2)--

Carbon dioxide, like carbon monoxide, is a product of the combustion of organic material. CO_2 is produced by natural sources (biological metabolism, volcanic eruptions) and by combustion of fossil fuels. Carbon dioxide is also a more stable molecule than is carbon monoxide, and CO tends to convert to CO_2 under ambient conditions. Monitoring studies indicate a gradual global increase in CO_2 levels, a high proportion of which result from escalating rates of fossil fuel combustion. Carbon that has been bonded in solid organic material is being released as a gas and thus may significantly change the composition of the earth's atmosphere. The current ambient CO_2 concentration is estimated to be between 335 and 340 ppm.

As a product of combustion the major enhanced recovery source of CO_2 is thermal operations. Generator and vehicular exhaust and in situ gas streams are the primary point sources.

Extensive research efforts are currently being undertaken to determine what effects the detected increases in CO_2 concentration could have on the environment. Some theories predict that a large increase in CO_2 in the atmosphere will trap heat and cause a potentially disastrous increase in global temperatures via the greenhouse effect.

Ozone and Other Photochemical Oxidants (O_3, O_x)--

Photochemical oxidants include ozone, NO_2, and peroxyacetylnitrate (PAN). They are produced by atmospheric reactions involving organic pollutants that is, hydrocarbons, nitrogen oxides (NO_x), oxygen and sunlight in a complex function of emissions and meteorological patterns. Because combustion processes produce volatile organics and NO_x, combination and photochemical formation of oxidants is likely. Regionalized oxidant concentrations are highest in urban areas, where they can reach levels in excess of 590 μg/m^3 (0.3 ppm). Rural peak concentrations are usually lower but can exceed 160 μg/m^3 (0.08 ppm) (U.S. EPA, 1978a).

Enhanced recovery combustion sources will also be the sources of photochemical oxidant components. Thermal operations including steam soak, steam drive, and in situ combustion are the technologies with the highest component emissions.

Steam generators are the major sources of organics and nitrogen oxides. However, in situ combustion emissions may also be high if venting of gases is not controlled.

Ozone and other photochemical oxidants have a detrimental effect on oxygen uptake, causing pronounced changes in lung function when performing light exercise after exposure to 0.75 ppm ozone. In subjects exercising maximally after 2 hours exposure to 0.75 ppm ozone with light exercise, decrements in maximum work load, tidal volume, heart rate and oxygen uptake were observed (U.S. EPA, 1978a).

Data on the quantitative relationships between ambient oxidant/ozone levels and precursor emissions are necessary for predicting the impact of these emissions on air quality. Air quality simulation models are currently being developed by EPA-funded studies for use in the formulation of policy for ozone control. However, because high NO_x concentrations and anthropogenic organics have been identified as the major contributors to severe oxidant/ozone pollution in urban areas, control of these emissions will be important to ozone control strategies (U.S. EPA, 1978a).

The present 1-hour National Ambient Air Quality Standard for photochemical oxidants is 160 $\mu g/m^3$ (0.06 ppm) (40 CFR 50). The California (1978) 1-hour standard is higher: 260 $\mu g/m^3$ (0.1 ppm) and therefore the federal standard supersedes it in this case.

Summary

Air emissions of SO_x, particulates, and NO_x from steam soak and steam drive processes exceed present standards. These are of concern and need to be analyzed to determine the relative costs and benefits of various control strategies. Fugitive emissions, which have not been sampled to any significant extent, are also of concern. H_2S is known to be a major pollutant from fugitive sources and potentially carcinogenic trace organics are also suspected of occurring in the fugitive emissions. Diagnostic sampling programs to fully characterize fugitive emissions are required. Finally, emissions from generators and motors employed in the enhanced recovery processes are generally not of significant volume to be of concern.

NOISE GENERATION

Oil and gas recovery involves activities that generate noise at moderate levels and occasionally at levels above recommended EPA and OSHA criteria levels. These include construction of roads and services, well drilling, and well servicing and workover. Most of these are intermittent sources that mainly impact workers. Concentrated sources in large wellfields are in many cases isolated from population centers.[41] Enhanced recovery processes involve the same noise generating activities with additional noise from water and chemical pumping facilities and steam generators. As a special case, chemical explosive fracturing involves subsurface explosions with associated surface tremors.

In general, noise is only of serious concern (1) during the initial phases of enhanced recovery projects when several construction activities occur concurrently; (2) during well drilling phases in residential areas when nighttime noise levels exceed EPA recommended levels, and (3) in major wellfields where closely spaced wells result in concentrations of noise generating equipment (pumps, steam generators, service vehicles). Guidelines for minimizing these impacts should be developed. The additional noise pollution of tertiary recovery over that conventional and secondary recovery is not generally significant. Most noise pollution caused by enhanced recovery falls under OSHA jurisdiction rather than EPA. Chemical explosive fracturing should undergo further EPA study.

Noise Impacts Methodology

Evaluation of environmental degradation resulting from noise relates to how the patterns of population occur in the vicinity of enhanced recovery projects. Figure 29 outlines the general methodology for a complete analysis. Such a methodology is best employed for specific sites using local data or for regions by developing regional models. This reports limits itself to the basic data that is available as inputs to those methodologies.

The analysis of the impacts of noise-creating activities includes consideration of (1) population impacts (on-site and off-site), (2) the degree of impact (dB level, duration), (3) available controls, and (4) the effects of these controls (effectiveness and cost).[42]

High noise levels are considered to be an environmental concern both because high intensity or long duration noise may cause eventual hearing impairment functionally related to distance from the source and because they are aesthetically annoying and interfere with other activities. According

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[41] Some exceptions to this general case need to be studied on a site specific basis.

[42] Items (3) and (4) are considered in Section 5 of the report.

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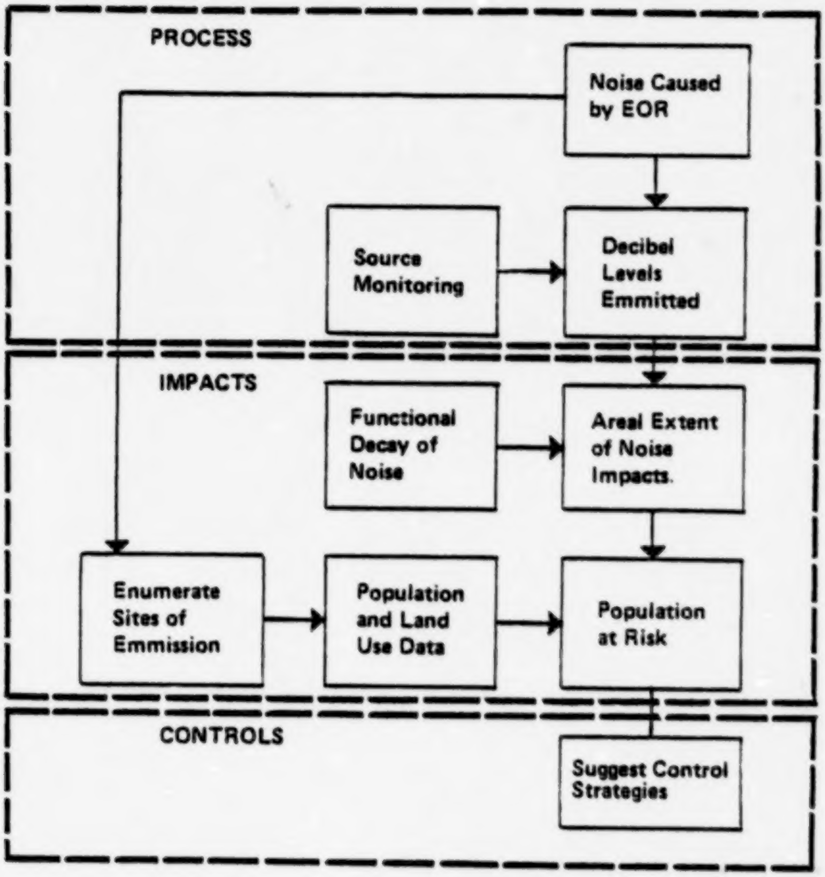
PAGE NUMBER
EPA-287 (Cin.)
(4-76)


PROCESS
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Functional Decay of Noise
Areal Extent of Noise Impacts.
Enumerate Sites of Emmission
Population and Land Use Data
Population at Risk
CONTROLS
Suggest Control Strategies

Figure 29. Noise impacts methodology.

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3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

to Bolt, Beranek, and Newman, Inc. (1976), studies of noise induced hearing impairment generally support the notion that the degree of impairment depends on both duration of exposure and intensity of noise. However, not all proposed environmental criteria interchange intensity and time in the same proportions. For example, OSHA regulations apply a 5-decibel increase for each doubling of exposure time while a rule of 3 decibels per doubling of time is advocated by the EPA.

The noise regulation potentially having most impact on EOR/EGR operations is included in the Occupational Safety and Health Act of 1970. The OSHA standard defines the levels of noise to which workers may be exposed and gives general direction to the employer for what to do if these levels are exceeded. The oil industry has not yet specifically been included in OSHA noise regulations, apparently because of the low labor to capital ratio of this industry as opposed to others. However, the standard developed by OSHA and eventually to be applied to the oil industry, permits employees to work eight hours a day on a job where the sound intensity is 90 dB (A).[43] This exposure, according to OSHA studies, is the maximum noise exposure that will not produce disabling loss of hearing in more than 20 percent of a population exposed through a working lifetime of 35 years. Reduced exposure time specified for greater intensities are shown in Table 19.

TABLE 19. PERMISSIBLE NOISE EXPOSURES IN THE WORKPLACE[a]

Duration (hours/day)	Sound Level dB(A), Slow
8	90
6	92
4	95
3	97
2	100
1-1/2	102
1	105
1/2	110
1/4	115

[a] OSHA Standards for Noise Exposure in the Workplace, Bureau of National Affairs, Washington, D.C.

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[43] dB(A) = decibels over ambient.

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3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The Noise Control Act of 1972 (PL92-574) provides the basis for the national environmental noise control program in the EPA. The act can be expected to only minimally affect enhanced recovery operations with the exception of noise from these operations that impacts neighboring activities. The relevant limits from this Act are shown in Table 20.

TABLE 20. SUMMARY OF NOISE LEVELS IDENTIFIED AS REQUISITE TO PROTECT PUBLIC HEALTH AND WELFARE WITH AN ADEQUATE MARGIN OF SAFETY[a]

Effect	Level	Area
Hearing loss	Leq[b] (24) ≤ 55 dB	All areas.
Outdoor activity interference and annoyance	L_{dn}[c] ≤ 55 dB	Outdoors in residential areas and farms and other outdoor areas where people spend widely varying amounts of time and other places where quiet is a basis for use.
	Leq (24) ≤ 55 dB	Outdoor areas where people spend limited amounts of time, such as schoolyards, playgrounds, etc.
Indoor activity interference and annoyance	L_{dn} ≤ 45 dB	Indoor residential areas
	Leq ≤ 45 dB	Other indoor areas with human activities such as schools, etc.

[a] EPA, Environmental Protection Agency Standards for Non-Ambient Noise Levels, PL 92-574.

[b] Leq (24) = Sound energy averaged over 24-hour period.

[c] L_{dn} = Leq with a 10-dB nighttime weighting.

Analysis of Available Data

Examination of oilfield activities has shown that most noise produced by EOR and EGR operations will originate from the following sources:

1. Drilling and repairing wells and casing
2. Diesel-powered generators
3. Compressor operation
4. Heavy equipment traffic
5. Pumps injecting fluids
6. Venting of high-pressured gas or steam.
7. Production and mixing of chemicals on-site.

Table 21 summarizes the available data on noise produced by these separate activities. However, in most fields a combination of the noise-producing sources will be operating simultaneously and compounding the dB level on and off-site. It might therefore be most useful to break down oil and gas recovery operations into the two phases of (1) construction and drilling, and (2) production to understand which noise sources will be of most concern to operators.

For example, the construction phase of enhanced oil and gas recovery will usually have most impact on neighboring activities because of the traffic and operation of heavy machinery to restructure the site for new modes of operation. Pipelines, for water, CO_2, and other resources, may have to be built, along with the drilling of wells, repairing of casings, and moving of materials. However, the resulting high noise and traffic levels should be of short duration, usually not more than several months. Traffic and construction activities are generally conducive to scheduling to avoid nighttime noise and minimize noise intensities if necessary. Drilling activities often must be on a 24-hour basis and may impose short-term burdens. The noise associated with equipment used in production is relatively continuous; however, levels are generally low enough to avoid the need for controls. On the other hand, venting of steam and gases associated with thermal recovery methods, if allowable from an air pollution standpoint, may require controls.

As Table 21 indicates, noise data for oilfield machinery are not complete. Noise levels of combined equipment will be specific to each operation, depending primarily on the scale of each operation, that is, the number of wells, the power of compressors and generators, and the amount of traffic. High noise levels are a recognized hazard to operators; some have been known to become prematurely deaf due to constant exposure to these noise levels. More complete data should be collected by the EPA and OSHA.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 21. SUMMARY OF NOISE IMPACTS[a]

	Pumps Injecting Fluid (M-P Flood)	Production of Chemicals On-Site (M-P Flood)	Drilling and Repairing Wells and Casings	Compressor Operation In Situ Combustion CO2 Flooding	Venting of High-Pressure Air, Gas, or Steam (In Situ Combustion CO2 Flooding)	Diesel-Powered Generators	Traffic (Heavy Equipment, Trucks)
Data availability							
Complete	x					x	
Incomplete		x	x		x		x
Nonexistent		x					
Preliminary assessment of impacts							
Clearly important				x		x	x
Probably important	x		x				
Probably unimportant		x					
Decibel range reported	76 dB at 50 ft		75-80 dB at 100 ft (diesel-powered drilling)	81 dB at 50 ft	105 dB	78-79 dB at 50 ft	91 dB at 50 ft (truck)
Decibel range with feasible controls	75 dB			75 dB	85 dB	75 dB	75 dB
Estimated frequency of occurrence	throughout	varying	sporadic short-term	throughout	throughout	throughout	varying
Available controls	Soundproof enclosure, portable barriers, EM protectors		Electric motors, portable barriers; ear protectors	Mufflers, portable barriers, ear protectors	Mufflers, electric motor Ear protectors		Schedule flooding
References[b]	2,3	2	2, p. 51	1,3			2,3

[a] Based on literature reviews.

[b] References:

1. U.S. Environmental Protection Agency; Federal Machinery Noise Research, Development and Demonstration, FY 1973-1975 (EPA 6k0012-75,000).
2. County of San Luis Obispo Office of Environmental Coordinator, Draft Environmental Impact Report for the Proposed Arroyo Grande Thermal Project; Teal Petroleum Co., California, 1978.
3. Kerbec, Matthew J.; Noise and Hearing, 1972.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

DEMAND FOR WATER BY ENHANCED RECOVERY PROCESSES

Introduction

Enhanced recovery processes involve extensive use of water for chemical injection, pressurized flooding, and steam injection. At present most enhanced recovery water use is consumptive. High quality water is required for chemical and steam injection. In the reservoir, these injected waters pick up a variety of mono and divalent ions. The resulting brines that are produced in ratios up to 20:1 are not suitable for reuse without extensive treatment.

The demand for water could become a serious impediment to the commercialization of enhanced recovery processes. This impediment can be overcome by use of water treatment and reuse systems. Pilot scale applications of these systems are under way (Wheeler, 1979).

The U.S. Water Resources Council is required under Section 13(a) of the Non-Nuclear Energy Research and Development Act (PL 93-577) to assess the water resources impact of new energy technologies and is planning an assessment of EOR activity in California and possibly on the Texas/Louisiana Gulf Coast.

General Description of Water Usage in EOR and EGR

Water plays an important role in most EOR technologies. Steam recovery operations require water to produce the steam used. The chemical flood processes (micellar-polymer, polymer, and alkaline) require water for use in preflushing the reservoir, formulating the chemical slugs, and in the follow-up water drive. Carbon dioxide miscible flooding processes currently in design stage call for water injection to immiscibly displace a CO_2 slug, or to raise the reservoir pressure to the level required for miscibility of the CO_2 with oil. Wet in-situ combustion involves the injection of water along with the air injected to supply oxygen to a burning front in the oil sand. In EGR, water is used in massive hydraulic fracturing but is not needed in chemical explosive fracturing.

In evaluating the significance of water usage in enhanced recovery processes, it is important to carefully take into account not only the total quantity of water used, but also the quality of water required and the potential for water reuse. Processes that can utilize low quality water or that can recycle a large proportion of the water used, present a much smaller water resource problem than do those processes requiring high quality water that is essentially irreversibly degraded in the course of being used.

It is also important to be aware that there is no hard and fast rule for classifying the usage of water in a particular recovery process as water consumption.[44] As a recovery technology evolves, there may well be a marked decrease in water consumption as new treatment technologies are developed or the recovery technology itself changes. For example, research in formulating brine-compatible surfactants or polymers may eliminate the necessity of freshwater preflushes. Thus the discussion in this report of the demand for water in enhanced recovery processes is designed primarily to draw attention to technologies that currently appear to have the potential for significant water consumption, rather than to determine definitive values for water consumption.

Water Law in Western States[45]

EOR operations, especially improved chemical, alkaline, micellar-polymer and steam flooding methods, will require large volumes of water over their lifetimes for injection into oil-bearing strata. This consumptive water resource use must be considered not only in the context of gross water availability, but also in terms of legal water allocation to these technologies in state water law.

Most of the regions in which intensive EOR development is currently taking place are in western states where water resources are also most limited. A generalization of western water law is presented here as background for the following discussion of water use needs and impacts.

Surface water--

Western states generally base surface water allocation and water rights on a doctrine of appropriation where the first applicant for a permit or first user is the first in right. Two fundamental principles of this doctrine include (1) that "beneficial use" of water must be a basis of a water right and that (2) the prior water user has the better right and may therefore be justified in a larger (though "reasonable") appropriation to satisfy his established requirements.[46]

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[44] The term "consumption" is often used to refer to the usage of high quality water with resultant degradation of quality which cannot be reversed in an economically feasible manner.

[45] General source: Gould, 1978.

[46] Definitions for "beneficial use" and "reasonable" may vary widely from state to state.

The effect of the rule of priority for water use is clear. Water shortages fall entirely on those who last gained access to water, rather than being borne by all users.

Groundwater--

Groundwater priority, unlike surface water priority, generally separates users from nonusers; those using an aquifer usually having equal rights to the water resource.

Permits--

Permits are required by western states (except Colorado) to establish a right to water use. Permits are usually administered by the State Engineer and, in California, also a Water Judge. These state administrator(s) enforce the priority system and generally control the use and distribution of water. Some significant provisions which might affect routine granting of a permit to an EOR operation include:

1. Interpretation of what constitutes a "beneficial use." EOR may in some circumstances be classified as not beneficial or not in the public interest and fail the "beneficial use" criteria.
2. State water planning legislation which is not structured to the allocation of water resources to enhanced flood operations.
3. State agency designation of preferential uses which prioritize water use to non-EOR uses when conflicts in water use arise.

Transfer of Existing Water Rights to New Uses--

In much of the West, water supplies are almost fully developed. Therefore, if new uses are to occur in these areas, it will be necessary to transfer water from existing uses. Generally, water may be transferred to a new place or purpose of use (in the states considered) if this transfer does not cause injury to existing (senior) appropriators. However, additional restrictions on transfer of water rights imposed by several states may have serious implications for EOR development in those states.

North Dakota, South Dakota, and Arizona have provisions in their water law that severely impede the transfer of irrigation rights to energy use. Because irrigation is the most likely source of water to be transferred to energy development, these provisions could be a serious limitation to water-intensive EOR development. Likewise, Montana also has provisions that seriously inhibit the transfer of water to EOR use. Consideration of public interest in Nevada and Wyoming and to some extent, though not expressly, in California, introduces an additional impediment to the transfer process. If widely and vigorously applied, this consideration can make transfer of water to EOR use more difficult in these states.

Thus, in North Dakota, South Dakota, Arizona, Montana, Nevada, Wyoming, and California, water access should be considered as an important aspect in water-intensive EOR development. Water rights are not always simply transferred; those proposing to transfer water to energy, and especially EOR technology users, often must be prepared for a difficult, expensive, and time-consuming process.

Review of Published Data

Little definitive analysis exists regarding availability of fresh water supplies for a commercialized enhanced recovery energy sector. The study by Braxton et al. (1976) reported on a preliminary basis that water supply problems existed for some EOR test projects; and that serious supply problems might develop. The San Francisco Office of the DOE has developed projections showing no serious supply problems for EOR activities in California reservoirs. DOE studies of water supply for energy development have not specifically analyzed the EOR technologies. EGR has been analyzed in a 1978 DOG Study (Booz, Allen, and Hamilton, 1978). Other general studies such as those by the OTA (1978), NPC (1976), and Schumacher (1978) have not provided any data. Thus, there is considerable need for some projections of realistic water demand; and there is need for a policy analysis of the priority of oil production consumption versus other uses in water shortfall states.

New Data

Quantitative data concerning freshwater usage in EOR and EGR processes were obtained from two principal sources: (1) the California Division of Oil and Gas; and (2) the DOE cost-sharing enhanced recovery projects.

California Division of Oil and Gas--

The California Division of Oil and Gas (DOG) publishes annual statistics regarding oil production and water injected as steam in steam recovery projects. The relevant 1976 data for the two principal California districts utilizing steam recovery, Districts 3 and 4, are shown in Tables 22 and 23. The geographical boundaries of the districts themselves are shown in the map in Figure 30.

The published statistics are of more value in indicating the total quantity of water used in steam injection than they are in giving an accurate picture of the ratio of water injected as steam to oil produced. As noted in the footnote to

TABLE 22. STEAM INJECTION OIL PRODUCTION DATA FOR 1976 (DISTRICT 3) CALIFORNIA[a]

Field	Volume Water Injected as Steam (bbl)	Oil Production (bbl)	Water Production (bbl)	Steam: Oil	Water Production: Oil Production
Arroyo Grande					
Tiber Area		124,346	447,572		3.60
Dollie	99,234			0.80	
Casmalia					
Monterey	347,534	618,860	9,980,470	0.56	16.1
Cat Canyon	5,946,687	6,752,494	26,537,546	0.88	3.93
Guadalupe	1,455,188	1,027,450	1,434,853	1.42	1.42
San Ardo					
Main Area	44,011,178	12,799,181	101,036,330	3.44	7.89
Total and averages	51,859,821	21,322,331	139,436,770	2.43	6.54

[a] CDOG, 1976.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 23. STEAM INJECTION DATA FOR 1976 (DISTRICT 4)[a,b]

Field	Volume Water Injected as Steam (bbl)	Oil Production (bbl)	Water Production (bbl)	Steam: Oil	Water Production: Oil Production
Belridge, North					
Shallow	738,615	347,999	1,208,448	2.12	3.47
Belridge, South					
Tulare-Diatomite	28,961,445	11,059,544	98,136,612	2.62	8.87
Cymric					
McKittrick Front Area, Tulare	1,112,317	915,847	10,121,109	1.21	11.1
Sheep Springs Area, Etchegoin	71,653	86,983	198,095	0.82	2.28
Welport Area, Tulare	2,455,969	1,538,846	10,351,549	1.60	6.73
Welport Area, Etchegoin	181,343	140,060	902,606	1.29	6.44
Edison					
Edison Groves Area, Chana	380,918	127,950	3,466,892	2.98	27.1
Main Area, Kern River-Schist	337,032	692,299	2,941,628	0.54	4.67
Race Track Hill Area, Kern River Transition	750,967	384,974	5,186,617	1.95	13.5
Northeast, Chanac	3,569	4,090	5,333	0.87	1.30
Kern Bluffs, Miocene	206,888	100,534	3,667,798	2.06	36.5
Kern Front					
Kern River-Chanac	3,096,029	3,960,996	45,806,774	0.78	11.6
Kern River					
Kern River	139,472,343	30,675,675	236,197,306	4.55	7.7
Lost Hills					
Tulare-Etchegoin	763,036	2,117,081	10,126,922	0.36	4.78
McKittrick					
Main Area, Upper	6,989,278	3,417,154	7,324,673	2.05	2.14
Northeast Area, Upper	2,690,623	1,316,885	5,753,275	2.04	4.37
Midway-Sunset					
Upper	49,208,976	38,224,489	85,768,620	1.29	2.24
Mount Poso					
Main Area, Vedder	13,001,342	3,632,605	83,047,006	3.58	22.9
Poso Creek					
Enas Area, Chanac	113,996	37,166	371,927	3.07	10.0
McVan Area		115,546	809,629		7.01
Etchegoin	158,130			1.37	
Premier Area		1,294,982	38,968,061		3.01
Etchegoin-Chanac	674,686			0.52	
Railroad Gap					
Amnicola	782,912	108,296	777,742	7.23	7.15
Wheeler Ridge					
Coal Oil Canyon	130,262	56,963	373,053	2.29	6.55
Totals and Means	252,282,330	100,293,960	651,511,670	2.52	6.50

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Notes to TABLE 23.

[a] CDOG, 1976.

[b] The steam/oil ratio is not a statistic of the Division of Oil and Gas but was calculated here by dividing the volume of water injected as steam by the oil production. The ratio, thus calculated, is likely to be an underestimate since oil production includes both oil produced in steam injection operations and oil produced in primary recovery operations. The statistics published by the California Division of Oil and Gas do not distinguish between the two categories. In addition, water injected as steam is frequently recorded for finer field subdivisions than is oil production. When this is the case, water injected as steam is shown here on the line following the data for oil production. This, of course, is also likely to result in an underestimate for the steam/oil ratio, since the oil production results from a larger field than that being operated with steam injection.

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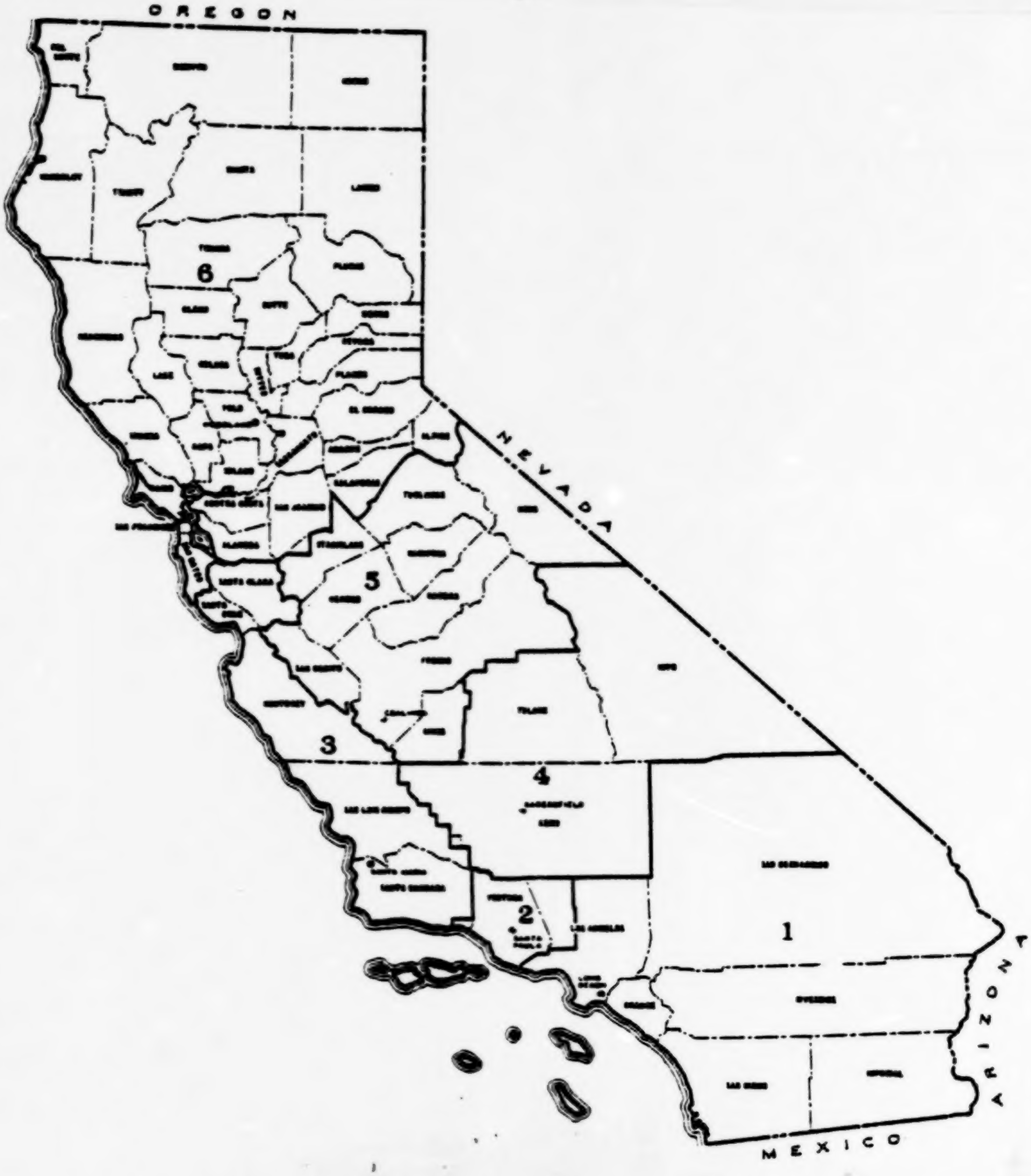

Figure 30. Oil and gas district boundaries and division of oil and gas offices. (California Division of Oil and Gas).

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EPA-287 (Cin.)
(4-76)

Table 23, the steam-to-oil ratio is likely to be an underestimate because the Division of Oil and Gas does not publish statistics on oil produced in steam-recovery operations alone, and furthermore, frequently records oil production for larger field areas than it does for steam injection. Nevertheless, some idea of the range of steam to oil ratios can be obtained. The range of steam injection to oil production ratio is seen from Table 23 to vary from 0.36 to 7.23 with a mean of 2.52 in District 4, and from 0.56 to 3.44 with a mean of 2.53 in District 3. This is a real variability and not a data problem. The wide variability in ratios occurs because of differences in reservoir variables including (1) oil viscosity, (2) reservoir permeability, (3) reservoir depth, and (4) waterflood history for the field.

The statistics on water production are included since they give an indication of the quantity of produced water that must be either treated and recycled or disposed of. The average ratio of water production to oil production in steam recovery projects is very close to the average ratio in oil production of all kinds. In District 4, the average ratio of water production to oil production in steam recovery projects was 6.50 compared to an overall ratio of 6.03. In District 3, the ratio of water production to oil production in steam recovery was 6.54 compared to an overall ratio of 7.52.

DOE Cost-Sharing Projects--

Of the DOE cost-sharing EOR projects only three were sufficiently advanced for any conclusions to be drawn regarding the relation of freshwater usage to oil production: (1) the micellar-polymer flood in North Burbank Field, Oklahoma; (2) the polymer flood in North Stanley Field, Oklahoma; and (3) the micellar-polymer flood in El Dorado Field, Kansas.

Micellar-polymer flood in the North Burbank Field--

In this project, operated by Phillips Petroleum Co., injection was initiated in December 1975. As of February 23, 1979, the quantities of fresh water injected were as follows (U.S. DOE, 1979c):

Pre-flush	2,369,000 bbl
Surfactant	294,000 bbl
Polymer	2,669,000 bbl
Fresh water buffer	3,179,000 bbl
Total	8,513,000 bbl

The total oil production as of February 23, 1979 was 205,411 bbl and the incremental oil production (i.e., that portion of the total oil production attributed to the micellar-polymer injection) was estimated to be 127,275 bbl. An additional

1,000,000 bbl of fresh water is scheduled to be injected and the projected total incremental oil production is estimated to be 250,000 bbl.

The ratio of fresh water injected to total oil produced to date is 41:4, while the ratio of fresh water injected to incremental tertiary oil produced to date is 66:9. The estimated ratio of fresh water injected to incremental tertiary oil over the entire project is 38:1.

Polymer Flood in the North Stanley Field--In this project, operated by Kewanee Oil Company, polymer injection was initiated in June 1976 and completed in June 1977. Freshwater injection was completed in October 1977 and saltwater reinjection was begun. The breakdown of freshwater injection is as follows (U.S. DOE, 1978m):

Pre-flush	3,979,334 bbl
Polymer	11,926,918 bbl
Flush	3,088,432 bbl
Total	18,994,684 bbl

Estimated oil recovery, both total and incremental tertiary, was:

Total	1,804,300
Total incremental	1,066,900 bbl

The ratio of fresh water injected to estimated total oil production is 10:5, and the ratio of fresh water injected to estimated total incremental tertiary oil production is 17:8.

Micellar-Polymer Flood in the El Dorado Field--Data were reported for two patterns, north and south. For both patterns, the project was still in its relatively early stages (U.S. DOE, 1978j). Micellar injection was still continuing for the north pattern and polymer injection had not yet begun for the south pattern. However, a streamtube oil recovery model had been used to compute oil recovery schedules for the two patterns so that a rough estimate could be obtained for the ratio of fresh water injected to oil recovered.

For the north pattern, the injection schedule calls for a total fluid injection after the micellar fluid of 2,800,000 bbl. Since the scheduled fluid injection preceding and including the micellar fluid is scheduled to be 806,360 bbl, this gives a total injected fluid volume of 3,606,360 bbl for the entire project. For the scheduled volume of injection up to and including the polymer stage, a figure of 1,393,530 bbl is given. This then is approximately the volume of water that is necessarily fresh. Of the remaining injected fluid, no indication is given as to whether it will be fresh or saline. As far as oil production is concerned, a set of curves is given that corresponds to different assumptions regarding the oil saturation remaining after the passage of the micellar slug made during running of the streamtube model. Cumulative oil production was calculated by using a planimeter to measure the areas under the oil production curves shown in Figure 31.

S_{orc}[47]	Cumulative oil production
0.0	364,056 bbl
0.15	187,038 bbl
0.20	124,692 bbl

For each value of cumulative oil production, two ratios of injected water to produced oil were calculated, one on the assumption that all fluid injected will be fresh, and the other on the assumption that fresh water will be used through the polymer stage only:

S_{orc}	Fresh water used for entire project	Fresh water used through polymer stage
0.0	9.91	3.83
0.15	19.3	7.45
0.20	28.9	11.2

For the south pattern, the total scheduled fluid volume is 2,945,902 bbl, and the scheduled fluid volume through the polymer stage is 999,952 bbl. The estimated oil production for different assumptions of remaining oil saturation is:

S_{orc}	Cumulative oil production
0.0	327,721 bbl
0.15	165,935 bbl
0.20	119,611 bbl

The ratios of freshwater injection to oil production are:

S_{orc}	Fresh water used for entire project	Fresh water used through polymer stage
0.0	8.99	3.05
0.15	17.8	6.03
0.20	24.6	8.36

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[47] S_{orc} is an oil saturation coefficient.

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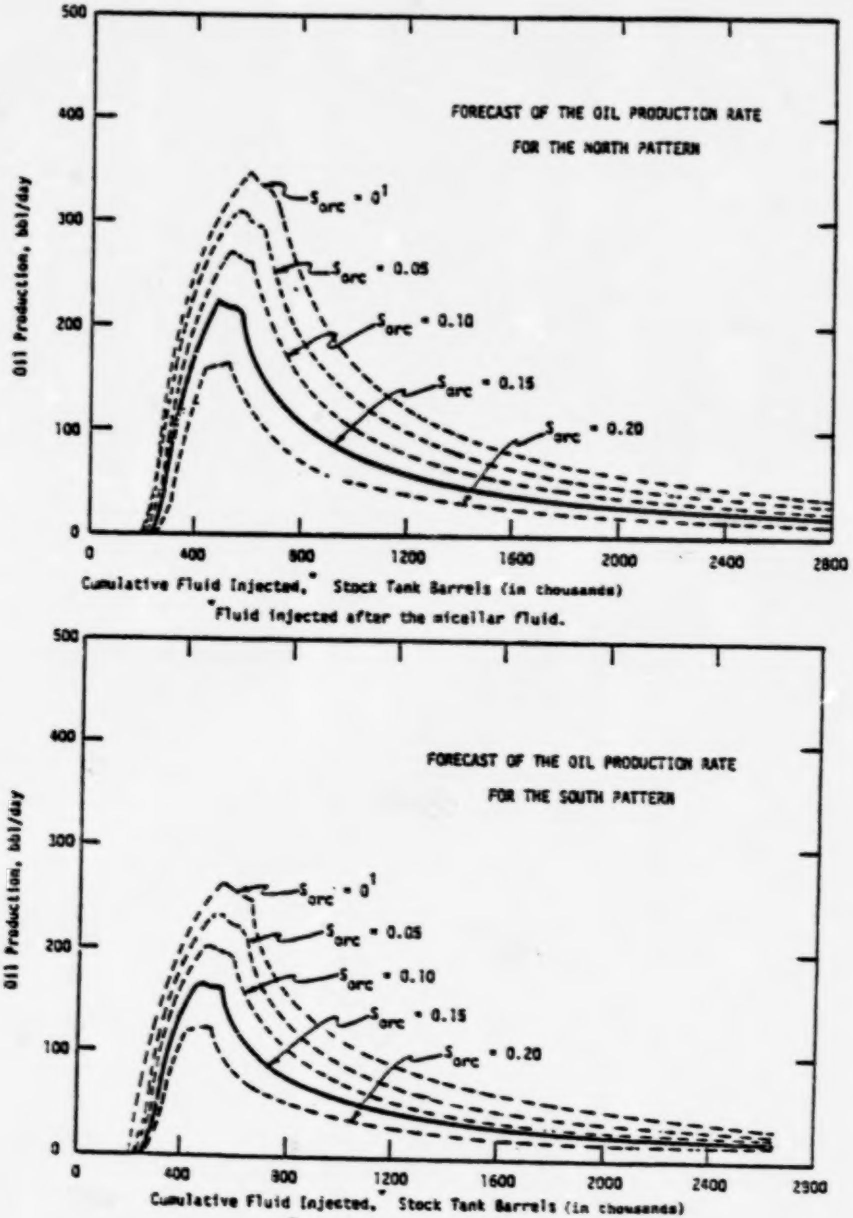

*Fluid injected after the micellar fluid.

[1] S_{orc} is an oil saturation coefficient.

Figure 31. Predicted oil production as a function of fluid injection for the El Dorado field. (U.S. DOE 1978j).

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EPA-287 (Cin.)
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As noted above, for both the north and south patterns, the ratios of water injection to oil production must be regarded only as rough estimates since they are based largely on computer modeling rather than on actual field data.

Water Needs Associated with Enhanced Gas Recovery

Requirements for freshwater supplies vary according to which enhanced gas recovery technology is being implemented. Massive hydraulic fracturing techniques require the largest supplies of fresh water, whereas chemical explosive fracturing requires virtually no input of fresh water. For gas stimulation by fracturing, all water injection is one time; that is, the fluid is injected to cause the formation to fracture and then is drawn back out and disposed of as a surface effluent. (This is in contrast to enhanced oil recovery methods in which water displaces oil in the reservoir and the flood is designed to be retained in the reservoir in place of the oil.)

In many cases, the gas-bearing shales are not suitable disposal sites for waste water. To date, all of the DOE funded fracturing projects have disposed of this waste water by way of so-called drilling pits, which are basically evaporating ponds for the waste water, sometimes employing liners which, upon evaporation, are filled and replanted.

The water use problem is a one-time problem for each level of each well that is hydraulically stimulated. Table 24 summarizes some representative data on the amount of water that can be expected to be used in different types of enhanced gas recovery projects. An analysis of the overall impact of the use of water in enhanced gas recovery was performed by the Lawrence Livermore Labs in their series of environmental reports. Their analysis concluded that water supplies, to be extracted from surface streams, would not constitute more than 10 percent of the stream flow at any time for most eastern shale sites. Their analysis was as follows.

While the flow volumes of the streams, and thus the impact of withdrawals for the project, vary widely from site to site, a "worst case" can be constructed from regional data. Stream flow is a function of the rate of runoff and the size of its drainage area. Annual runoff in the region ranges from 10 in. in eastern Ohio to over 30 in. in eastern West Virginia. Since 1 in. of runoff over 1 mi^2 equals about 1.74×10^7 gal, a stream in the driest part of the region with a drainage area of only 2 mi^2 would have an average flow of 2.89×10^9 gal/mo, of which the maximum of 300,000 gal represents only 1 percent. This does not, of course, reflect seasonal variations in flow, which in August, September, and October can drop to under 10

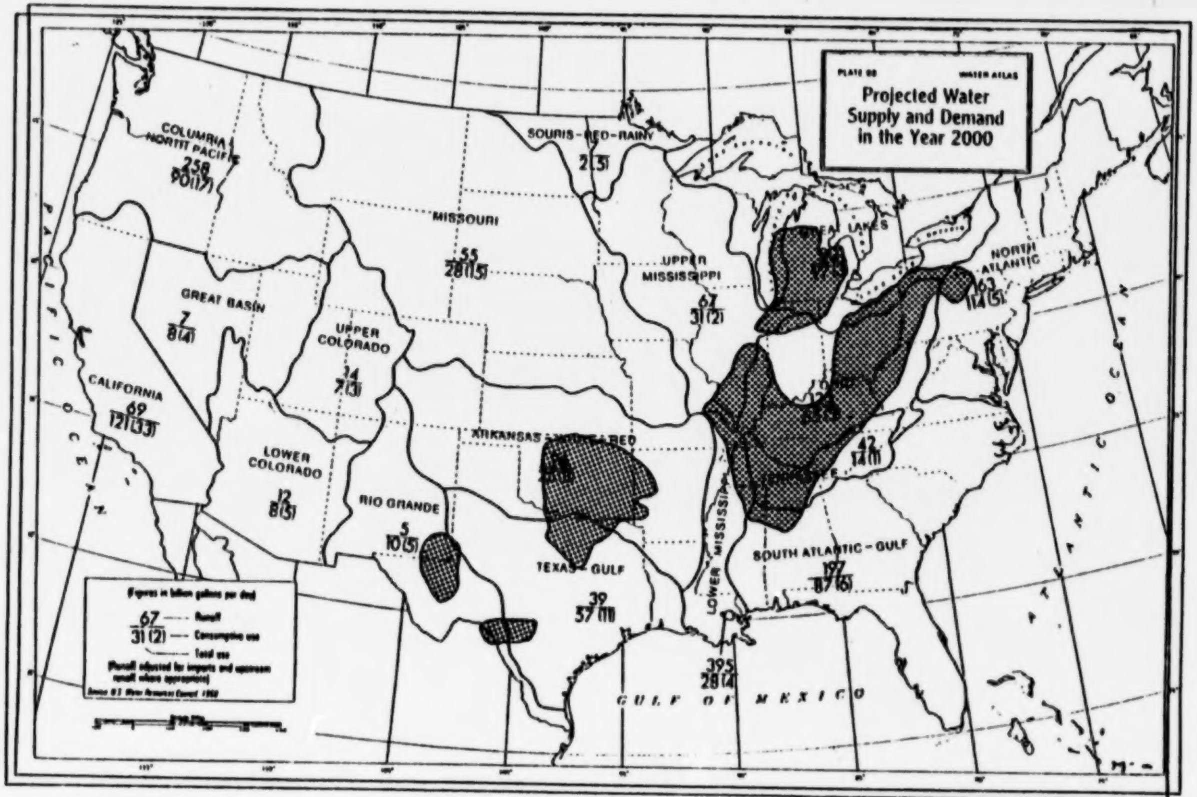
TABLE 24. WATER REQUIREMENTS FOR EGR

Technology	Total Fluids (bbl/well)	Water Use (bbl/well)	Expected Yield (CF)	Ratio (bbl/CF)
Cryogenic	1,140-3,040	896-2,280		
Conventional	1,900	1,900	NA	NA
Conventional-Foam	1,900	380	NA	NA
Massive hydraulic fracturing	10,000-19,000	10,000-19,000	NA	NA
MHF-Foam	10,000-19,000	2,000-3,800	NA	NA
Dendritic	4,028-16,960	4,028-16,960	NA	NA
Chemical explosive fracturing	50	50	NA	NA

percent of the average. However, most streams have drainage areas covering tens or hundreds of square miles, and thus significantly larger volumes. Moreover, since the fracture water will be pumped to storage tanks on site prior to its use, the rate of pumpage will be adjusted so that streamflow is not reduced by more than 10 percent at any time.

However, the situation is somewhat different for western shale reserves in Oklahoma and Texas that coincide with areas of regional water deficits. Figure 32 shows the occurrence of shale resources as they relate to regional water availability.

The real overall impact of water use in enhanced gas recovery will depend upon the expected gas reserves which can be tapped and the expected intensity of well drilling which can occur in a given field. Figure 33 presents an analysis of the expected yield of enhanced gas recovery. The projections presented in that figure suggest that fracturing of gas shales will be greatly accelerated in the next 20 years, considerably multiplying the present levels of environmental impact. In particular, the current projects are mainly pilot efforts in shales that are highly conducive to fracturing. When networks of wells are located in a particular zone or area, the cumulative local water burden may become more significant; also, some of the shales to be fractured later in the development of the technology may require substantially more than 300,000 barrels of water per well to accomplish the fracture. Spacing of wells


Projected Water Supply and Demand in the Year 2000
COLUMBIA - NORTH PACIFIC
258
90(17)
SOURIS - RED - RAINY
2(.5)
MISSOURI
55
28(15)
UPPER MISSISSIPPI
67
31(2)
GREAT LAKES
NORTH ATLANTIC
63
11(4)(5)
GREAT BASIN
7
8(4)
UPPER COLORADO
14
7(3)
CALIFORNIA
69
121(33)
LOWER COLORADO
12
8(5)
RIO GRANDE
5
10(5)
ARKANSAS - WHITE - RED
TEXAS - GULF
39
37(11)
LOWER MISSISSIPPI
395
28(4)
TENNESSEE
42
14(11)
SOUTH ATLANTIC - GULF
197
87(6)
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
67 — Runoff
31 (2) — Consumptive use
— Total use

▨ Major Gas Shale Deposits

(U.S. Water Atlas)

Figure 32. Overlay showing relationship of gas shale deposit locations to water availability patterns.

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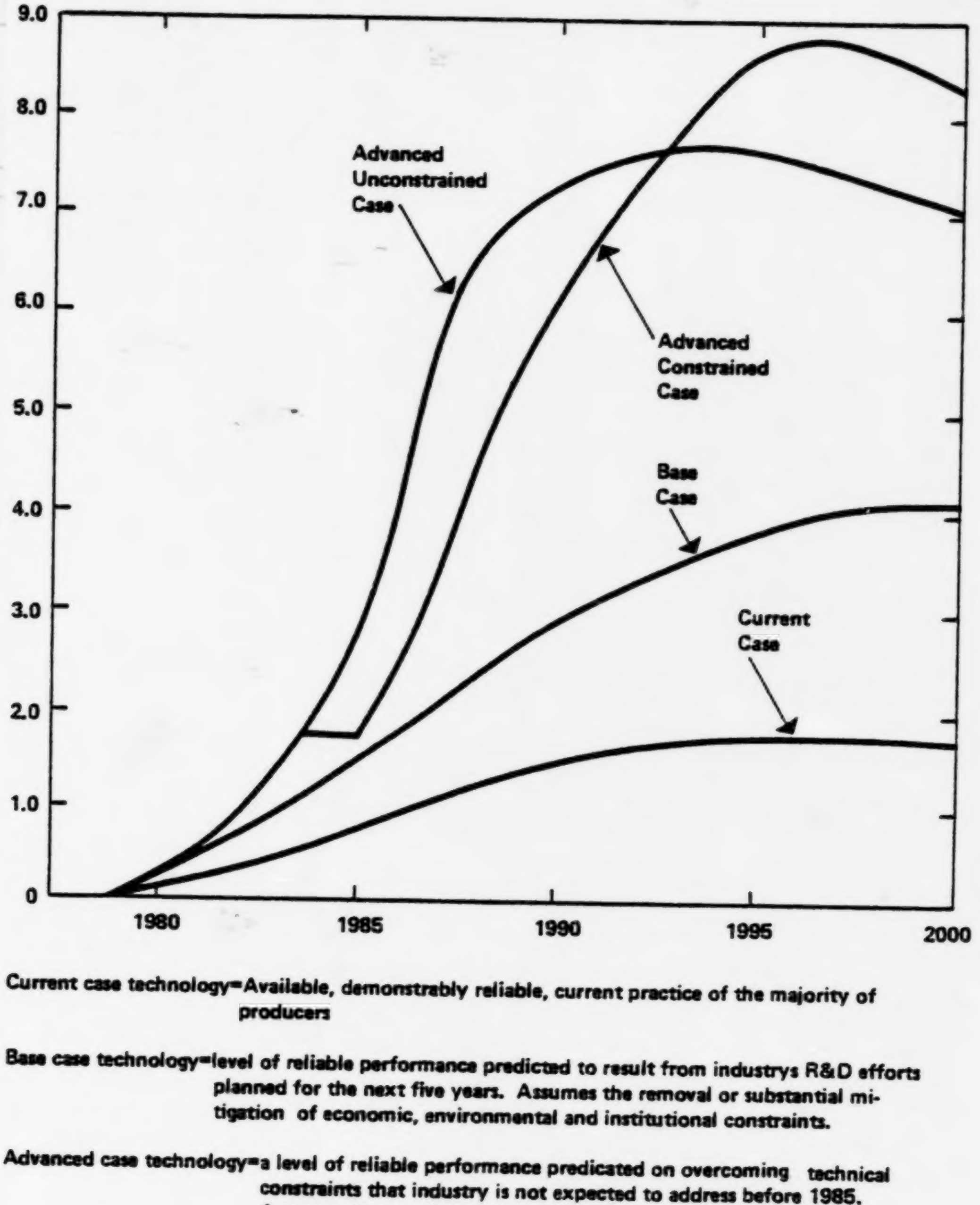

Current case technology=Available, demonstrably reliable, current practice of the majority of producers

Base case technology=level of reliable performance predicted to result from industrys R&D efforts planned for the next five years. Assumes the removal or substantial mitigation of economic, environmental and institutional constraints.

Advanced case technology=a level of reliable performance predicated on overcoming technical constraints that industry is not expected to address before 1985. Assumes vigorous federal initiatives and removal or substantial mitgation of non-technical constraints.

Figure 33. Annual production from unconventional sources of natural gas (at NEA prices). (U.S. DOE, 1978b).

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EPA-287 (Cin.)
(4-76)

will be constrained in particular for chemical explosive fracturing in which damage to neighboring wells must be avoided.

Comparative Water Consumption

It is of considerable interest to compare water consumption in EOR with water consumption in other technologies for producing fuels in order to get some idea of the relative water requirements posed by EOR. Here we present some data obtained for water consumption in technologies for coal conversion and shale oil recovery, and derive a conversion factor for facilitating comparison of data for water consumption in EOR technologies with data for water consumption in other fuel-producing technologies.

The two sources used to obtain data on water consumption in coal conversion and oil shale technologies were Harte and El-Gasseir (1978) and Probstein and Gold (1978).

Table 25 is adapted from Harte and El-Gasseir (1978). In their article, water consumption is given in units of cubic kilometers per 10^{18} joules of synthetic fuel product. In Table 26, we have converted these values to units of gallons per million Btu of synthetic fuel product by multiplying the figures of Harte and El-Gasseir by the conversion factor of 278.66.[48]

Table 26 is based on Probstein and Gold (1978). It will be noted that the range of values given by Probstein and Gold is in general considerably lower than that given by Harte and El-Gasseir. One reason for this may be that Probstein and Gold assume that total recycling is feasible. In their words, "all effluent streams are assumed to be recycled or reused within the mine or plant after any necessary treatment. These streams include the dirty waters generated in the conversion process and the highly saline water drawn off (blown down) from wet evaporative cooling towers. Water only leaves the plant as vapor, as hydrogen in the hydrocarbon products, or as occluded water in the solid residues. Dirty water is cleaned, but only for reuse and not for returning it to a receiving water."

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[48] The conversion factor is derived as follows

$$\frac{1\ \mathrm{km}^3}{10^{18}\mathrm{J}} = \frac{1\ \mathrm{km}^3}{10^{18}\mathrm{J}} \times \frac{10^9\ \mathrm{m}^3}{\mathrm{k}^3\mathrm{m}} \times 264.173\ \frac{\mathrm{gal}}{\mathrm{m}^3} \times \frac{1}{9.480 \times 10^{-10}\ \frac{10^6\ \mathrm{Btu}}{\mathrm{J}}}$$

$$= 278.66\ \frac{\mathrm{gal}}{10^6\ \mathrm{Btu}}$$

EPA-287 (Cin.)
(4-76)

TABLE 25. WATER CONSUMPTION (GAL/10^6 BTU) IN COAL CONVERSION AND SHALE OIL EXTRACTION[a]

	Category of Use						
	Mining	Reclamation	Transport by Slurry Pipelines	Conversion	Associated Urban	Total with Slurry Pipelines	Total Without Slurry Pipelines
Low-Btu gas							
Eastern coal							
Surface-mined	0.780-0.975	0.0-8.36	12.5-15.9	23.1-162	5.01	41.8-192	27.9-176
Deep-mined	1.73-2.17	0.0	12.5-15.9	23.1-162	5.01	41.8-184	30.6-170
Western coal							
Surface-mined	0.780-1.95	0.780-39.0	12.5-30.6	23.1-162	5.01	41.8-240	30.6-206
Deep-mined	1.73-2.79	0.0	12.5-30.6	23.1-162	5.01	41.8-201	30.6-170
High-Btu gas							
Eastern coal							
Surface-mined	0.975-1.17	0.0-10.0	15.9-19.2	23.1-162	13.7	52.9-206	39.0-187
Deep-mined	2.17-2.65	0.0	15.9-19.2	23.1-162	13.7	55.7-198	39.0-178
Western coal							
Surface-mined	0.975-2.37	1.00-47.4	15.9-39.0	23.1-162	13.7	55.7-265	39.0-226
Deep-mined	2.17-3.34	0.0	15.9-39.0	23.1-162	13.7	55.7-195	39.0-178
Syncrude							
Eastern coal							
Surface-mined	0.863-15.9	0.0-13.4	14.2-25.9	30.6-206	8.08	52.9-256	39.0-228
Deep-mined	1.95-3.62	0.0	14.2-25.9	30.6-206	8.08	55.7-245	41.8-217
Western coal							
Surface-mined	0.863-3.06	0.891-64.1	14.2-52.9	30.6-206	8.08	55.7-334	39.0-279
Deep-mined	1.95-4.74	0.0	14.2-52.9	30.6-206	8.08	55.7-273	39.0-220
Oil from shale							
Surface technology							
Surface-mined	1.11-1.56	9.19-14.8	NA	8.36-12.3	1.92-2.56	NA	20.6-30.6
Deep-mined	1.14-1.56	8.91-15.6	NA	8.36-12.3	2.28-3.06	NA	20.6-33.4
In-situ technology							
Modified in situ	0.529-1.724	3.90-8.36	NA	7.52-13.1	2.42-2.79	NA	14.5-25.1
True in situ	NA	8.8-2.14	NA	8.8-13.3	2.45-2.79	NA	2.51-17.3

[a] Harte and El-Gasseir, 1978.

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EPA-287 (Cin.)
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TABLE 26. WATER CONSUMPTION (GAL/10^6 BTU) IN COAL CONVERSION AND SHALE OIL RECOVERY[a]

	Category of Use						
	Net Process	Cooling	Mining, Disposal, and Other	Flue Gas Desulfur-ization	Retorting and Upgrading	Spent Shale Disposal	Total
Hygas	6.21-8.76	10.1-13.3	1.41-4.24	1.13-1.69	NA	NA	23.2-24.0
Lurgi	-1.69-5.65	16.9-19.2	1.13-5.08	1.69-2.82	NA	NA	22.0-29.4
Synthane	4.52-5.08	13.0-15.8	1.13-3.95	1.13-3.39	NA	NA	22.6-27.7
Synthoil	1.59-3.58	12.7-15.5	1.59-6.76	NA	NA	NA	16.7-21.9
Solvent refined coal (SRC)	-0.771-1.16	7.32-7.71	1.73-6.74	NA	NA	NA	9.63-15.0
Oil shale	NA	8.50-13.2	2.55-4.25	NA	-0.85-2.55	5.10-14.5	18.3-28.9

[a] Probstein and Gold, 1978.

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EPA-287 (Cin.)
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To compare water consumption in EOR with water consumption in other fuel-producing technologies, it is important to express water consumption in the same units, such as gallons of water used per million Btu of heating value of the fuel product. Most EOR data on water consumption are available in terms of water volume consumed or used per volume oil recovered; for example, gallons of water per gallons of oil recovered. To convert this ratio to gallons of water per million Btu's it is necessary to divide by the number of million Btu per gallon of oil, or, equivalently, to multiply by the number of gallons of oil per million Btu's of heating value. Table 27 gives the heat of combustion for representative crude oils from various geographical regions, along with the resulting multiplicative factor for converting water consumption on a volume-to-volume basis to water consumption expressed in terms of gallons per million Btu's. A conversion factor equal to approximately 7 appears quite reasonable.

TABLE 27. HEAT OF COMBUSTION OF CRUDE OILS AND MULTIPLICATIVE FACTOR FOR CONVERTING WATER CONSUMPTION (VOLUME WATER PER VOLUME OIL RECOVERED) TO UNITS OF GALLONS WATER PER MILLION BTU HEATING VALUE OF OIL RECOVERED[a]

Crude Oil	Btu/lb	lb/gal	Btu/gal	Conversion Factor (gal oil/10^6 Btu)
California	18,910	7.636	144,397	6.9
Kansas	19,130	7.670	146,727	6.8
Oklahoma	19,502	7.236	141,116	7.1
Texas	19,460	7.286	141,786	7.1

[a] CRC Handbook of Chemistry and Physics, 35th Edition, 1953, p. 1754.

Using this conversion factor we can compare the data on EOR water usage given in the previous section with the data on water consumption in coal conversion and shale oil recovery presented above. For California steam recovery, we have the following water usage expressed in units of gallons per million Btu's of oil recovered:

	Range	Mean
District 3	3.92-24.1	17.0
District 4	2.52-50.6	17.6

For the micellar-polymer flood in the North Burbank Field, the estimated freshwater usage is 267 gallons of water per million Btu's of incremental tertiary oil. For the polymer flood in the North Stanley Field, the estimated freshwater usage is 73.5 gallons per million Btu total oil recovered and 125 gallons of water per million Btu's of incremental tertiary oil recovered. For the micellar-polymer flood in the El Dorado Field, the estimated freshwater usage ranges from 21.4 to 172 gallons per million Btu's of total oil recovered.

Comparing these figures with the water consumption data given by Probstein and Gold (1978) for coal conversion and shale oil recovery (Table 26), we see that water usage in California steam recovery is very similar to that in coal conversion and shale oil recovery. Actually, the California steam recovery water consumption is probably considerably lower than the water usage, since in Kern County at least, the major California steam recovery area, much of the produced water is recycled.[49] This recycling is not reflected in the California Division of Oil and Gas data.

Water usage in the three EOR chemical flood projects discussed is seen to be considerably higher than that in California steam recovery. It is comparable to the mid- to upper-range of the data for water consumption in coal conversion and shale oil recovery given by Harte and El-Gasseir (Table 25). Admittedly the sample of DOE cost-sharing projects available to us here is very small and the data available to this project are limited. Nevertheless, the data that are available appear to indicate that chemical flood EOR processes can use substantial quantities of water and that if the supply of fresh water is anticipated to be a limiting factor in EOR, it will be important to extensively utilize treatment and recycling or to develop brine-compatible chemical floods.

---

[49] According to Fred Hallmark of the California Division of Oil and Gas in Sacramento, the geology of the Kern River oil field is very unusual in that the oil is found in conjunction with a freshwater aquifer whereas most oil is found in brackish aquifers. Prior to steam recovery having been introduced, the produced water from primary recovery in Kern County was actually discharged into the Kern River system and used by farmers. Relatively little treatment is required in order to recycle the produced water for steam recovery.

EPA-287 (Cin.) (4-76)

DEGRADATION OF GROUNDWATER

Enhanced recovery can result in contamination of aquifers by a variety of pathways that fall into three general categories: downward leaching from surface disposal, communication to aquifers via improperly sealed or cased wells, and communication to aquifers through fractures or cracks in previously impermeable formations Such fractures may be opened up by changed reservoir pressures accompanying enhanced oil recovery techniques and subsequent reinjection or by gas fracturing. Figure 34 depicts the major routes of contamination.

Evaluation of existing information can only provide tentative conclusions regarding groundwater degradation. Significant risk appears to exist. Some of the chemicals employed in enhanced recovery may be toxic or carcinogenic. Little is known about the degradation products of these chemicals, which may be more or less toxic than the parent chemicals. Brines, which are produced in as high as a 20:1 ratio with oil in current enhanced recovery operations, have the potential to contaminate freshwater aquifers by reinjection or disposal. Brines also contain heavy metals that may migrate from the disposal site. Some of the pathways depicted in Figure 33 are known to exist as a result of pollutant events that have already occurred. Others only represent possible pathways. The volumes and concentrations of chemicals used are significant enough to warrant further investigation of the toxicities of the chemicals and of the pollutant pathways.

Groundwater Impacts Methodology

A general impacts assessment scheme has been developed and is displayed in Figure 35. Table 28 compares this methodology with a methodology employed in a recent DOE monitoring guidelines study (Booz, Allen & Hamilton, 1978). The current study attempts to assess what levels of control are needed for adequate environmental protection. Many environmental concerns are not clearly covered by current regulations. The DOE study was restricted to compliance with existing regulations.

Overall Approach--

The EPA and DOE have two main requirements for evaluation of groundwater pollution. One is an assessment of the technology-wide impacts of enhanced recovery to allow comparison of the environmental risks of various energy sources. The other is a procedure for evaluating and approving/disapproving specific projects. The methodology laid out in Figure 35 is general enough to be adapted for either use. It is specifically intended to provide a technology-wide assessment.

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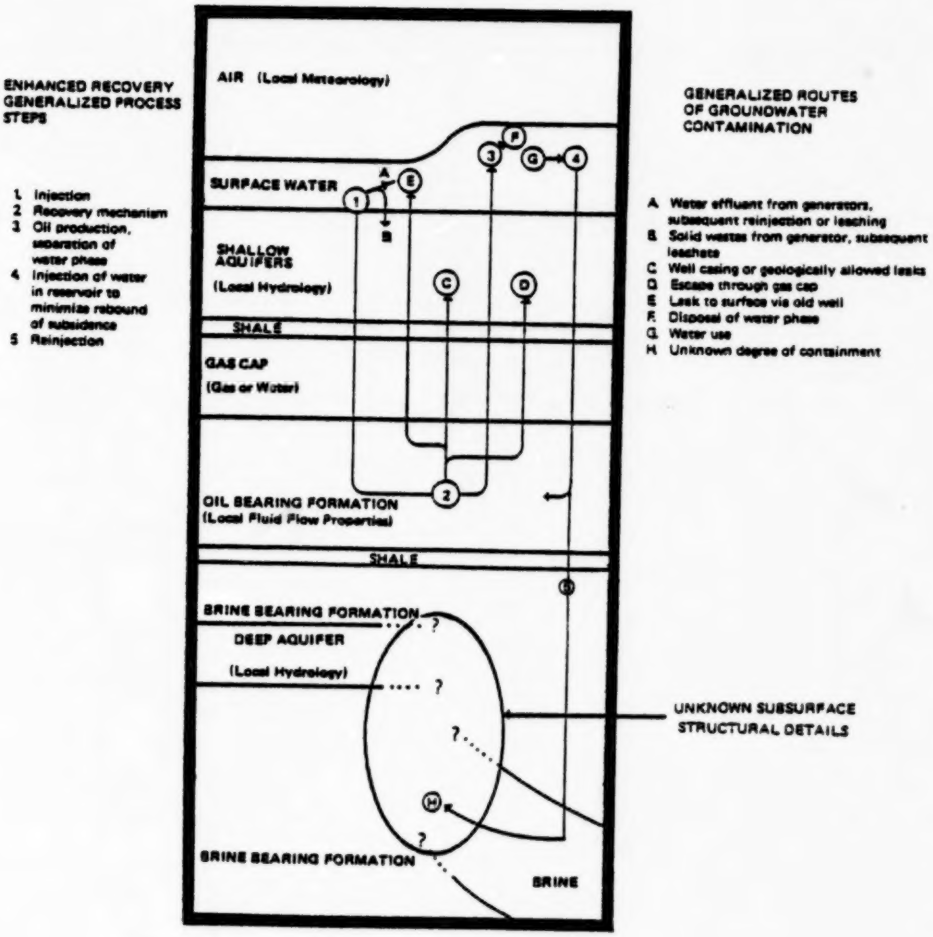
ENHANCED RECOVERY GENERALIZED PROCESS STEPS
1 Injection
2 Recovery mechanism
3 Oil production, separation of water phase
4 Injection of water in reservoir to minimize rebound of subsidence
5 Reinjection
AIR (Local Meteorology)
SURFACE WATER
SHALLOW AQUIFERS
(Local Hydrology)
SHALE
GAS CAP
(Gas or Water)
OIL BEARING FORMATION
(Local Fluid Flow Properties)
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BRINE BEARING FORMATION
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GENERALIZED ROUTES OF GROUNDWATER CONTAMINATION
A Water effluent from generators, subsequent reinjection or leaching
B Solid wastes from generator, subsequent leachate
C Well casing or geologically allowed leaks
D Escape through gas cap
E Leak to surface via old well
F Disposal of water phase
G Water use
H Unknown degree of containment
UNKNOWN SUBSURFACE STRUCTURAL DETAILS

Figure 34. Major routes of groundwater contamination associated with enhanced recovery.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

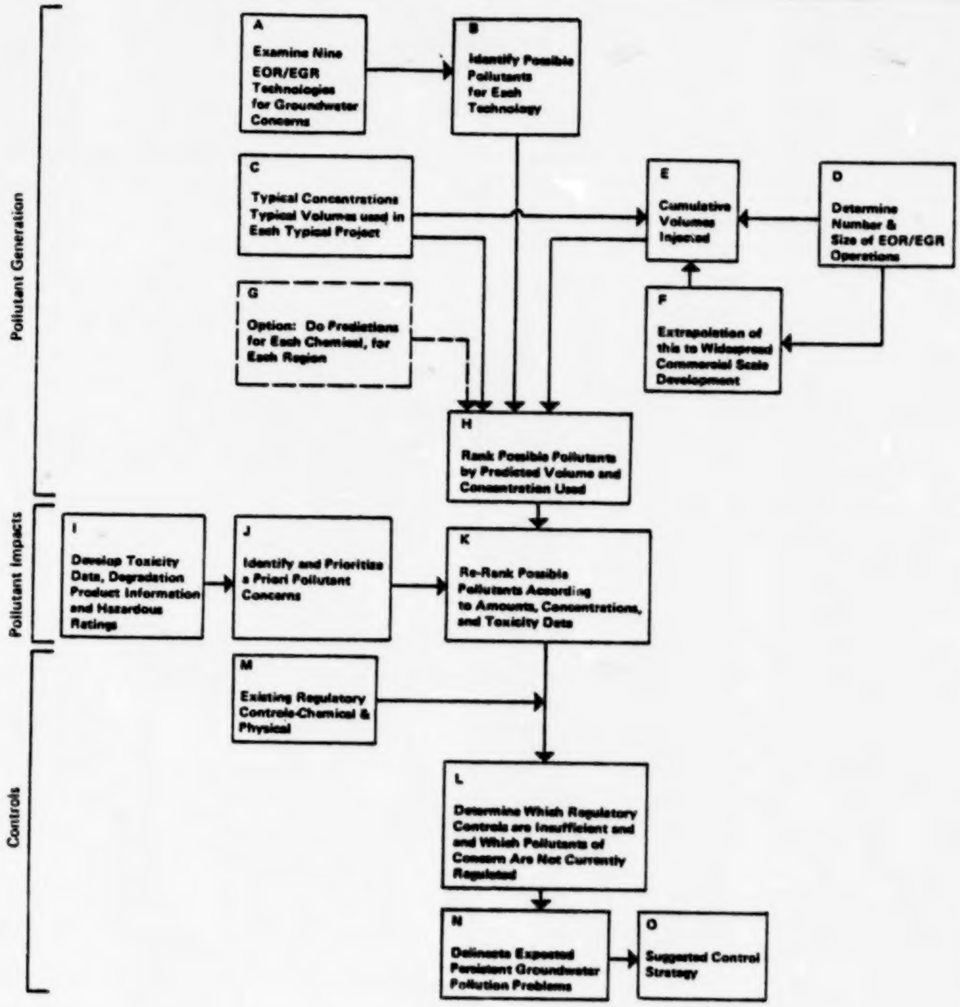
Pollutant Generation
Pollutant Impacts
Controls
A
Examine Nine EOR/EGR Technologies for Groundwater Concerns
B
Identify Possible Pollutants for Each Technology
C
Typical Concentrations Typical Volumes used in Each Typical Project
E
Cumulative Volumes Injected
D
Determine Number & Size of EOR/EGR Operations
G
Option: Do Predictions for Each Chemical, for Each Region
F
Extrapolation of this to Widespread Commercial Scale Development
H
Rank Possible Pollutants by Predicted Volume and Concentration Used
I
Develop Toxicity Data, Degradation Product Information and Hazardous Ratings
J
Identify and Prioritize a Priori Pollutant Concerns
K
Re-Rank Possible Pollutants According to Amounts, Concentrations, and Toxicity Data
M
Existing Regulatory Controls-Chemical & Physical
L
Determine Which Regulatory Controls are Insufficient and and Which Pollutants of Concern Are Not Currently Regulated
N
Delineate Expected Persistent Groundwater Pollution Problems
O
Suggested Control Strategy

Figure 35. Groundwater impacts methodology. This figure outlines a general scheme for assembling scientific and regulatory data to evaluate risks of groundwater pollution. Some of the steps in the analysis can be performed now (A, B, I, M) and some can only tentatively be done pending commercialization, (C, D, E, F). The remaining steps can be done using qualitative estimates but actually require a much more extensive data base to be carried out accurately, (H, J, K, L, N, O). Step "G" involves investigation of specific projects.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 28. COMPARISON OF ANALYTICAL TASKS OF THE BOOZ-ALLEN DOE STUDY AND THIS EPA STUDY[a,b]

This Study	DOE (Booz-Allen)
A. Examine the nine EOR/EGR technologies for groundwater concerns. B. Identify possible pollutants for each technology.	Figure 1-1, Pollutant selection logic diagram. 1. Identify potential pollutants.
C. Determine typical volumes used in each type of project. D. Determine number and size of EOR/EGR operations at present. E. Determine cumulative volumes of each chemical injected. F. Extrapolate typical EOR production levels to a widespread commercial scale. G. Rank possible pollutants by predicted volume and concentrations used, or to be used. H. Develop toxicity data, degradation product information, and hazardous ratings. I. Identify and prioritize the pollutant concerns. J. Rerank possible pollutants according to amounts used, concentrations, and toxicity data. K. Determine insufficient regulatory controls or priority pollutants not regulated at all.	2. Identify regulations or laws governing release of identified pollutants. 3. Determine if existing law governs the substances release.
	3a. Characterize significance of release relative to applicable standard. 3b. Is magnitude of release significant relative to standard? If so, drop from further consideration.
L. Analyze existing regulatory controls: (1) chemical; (2) physical. M. Delineate expected persistent groundwater pollution problems.	
N. Suggest control strategies for those emissions that do exceed existing laws, those that may violate pending laws, and those that are not regulated but pose a threat.	3c. Develop monitoring guidelines for pollutants. 4. Determine whether pending regulations or laws are likely to affect release of identified pollutant. 4a. Characterize significance of release relative to likely standard. 4b. Drop from further consideration if magnitude of release is not significant. 5. Characterize risk associated with release of constituent. 6. If unknown suggest more R&D done on that chemical. 7. Drop from further consideration if risk is negligible. 8. If not, characterize significance of release relative to possible effects. 9. Recommend monitoring to forestall delays in commercialization. 10. Develop monitoring guidelines for pollutants.

[a] The DOE study was specifically designed to identify ways of complying with existing regulations. This EPA study has a different and much broader task. Namely, this study must look at pollutant processes that are of significance but that are not now covered by environmental regulations. Hence the project's analytical tasks are broader in scope and cover possible pollutant pathways that are not approachable by regulations.

[b] Arrows indicate comparable tasks.

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EPA-287 (Cin.)
(4-76)

Technology-wide and project-specific impacts cannot be easily distinguished in the case of enhanced recovery. Each project and reservoir presents a site-specific set of groundwater concerns. Hence a technology-wide assessment is best carried out by extrapolation from a representative group of site-specific studies. For many of the technologies, polymer/micellar and alkaline in particular, the population of completed field tests is small enough to allow a reasonable probability that the group of studies available for analysis is unrepresentative. Thus, the quality of environmental data and analysis can be expected to improve significantly over the next few years as the current field projects begin to be completed.

The intent of the approach delineated here is to move away from the use of unannotated lists of pollutants, lists of pollutant pathways, and lists of potential impacts. This can be accomplished by development of information regarding volumes discharged, toxicity levels, and transport. After these data are obtained, specific problems that present unacceptable hazard levels can be identified and controlled. The major aspects of the approach are to:

1. Characterize the use of potential groundwater pollutants in specific projects. The first step of the analysis involves tasks (A), (B), (C), and (G) of the proposed methodology. The key analytical problem is selection of a representative set of projects to study. This will require evaluation of the injection program selected, the reservoir geology, the production history of the field, and the local environment. The characterization will require a complete set of data for these projects on the volumes and concentrations of chemicals used, injection pressure, and the like.

2. Project the nationwide level of EOR activity. This step of the analysis, involving tasks (D), (E), (F), and culminating in the interpretive analysis of task (H), will depend upon energy policy assumptions. Key assumptions include oil prices, speed of solutions to technological impediments, and chemical supply. Task H requires development of a set of acceptable ranking criteria.

3. Evaluate human health hazards. Tasks (I), (J), and (K) involve the assessment of the toxicity associated with the suite of EOR pollutants.

4. Develop an assessment of the pollutant problem. The information developed in the first three steps

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

of the analysis must then be analyzed in terms of relative health risks. This analysis must incorporate a number of external factors including currently allowable levels of hazard, risks imposed by other options for energy supply, availability of control technology, and analytic uncertainties. This involves tasks (L), (M), and (N).

5. Recommend controls. The final outcome of the analysis is a proposed series of controls. Task (O) must involve an investigation of the energy, economic, environmental, and social costs and benefits of several possible approaches.

Application of the Methodology to Individual Site Impact Assessments--

In adapting the proposed methodology to individual site evaluations, particular attention must be given to the specific pollutants generated and the specific local environment. Patterns of human use of the areas and groundwater must be compared with patterns of potential contamination. This can then provide an indication of the population at risk. It should be noted that many projects occur in remote areas. However, in the case of sole source aquifers[50] very stringent controls are always required.

For most sites, groundwater hydrology is not well understood. Hence, significant pollutant transport must be considered a possibility. In any site-specific assessment, all NEPA requirements must be met, some of which are not specifically laid out in our methodology.

Preliminary Assessment Based on Existing Data

Currently existing information is inadequate for an application of the methodology laid out above. Presented below are the various portions of the analysis which could be assembled with existing data. In many cases the results are only preliminary. The important data gaps are due to (a) the lack of environmental monitoring, (b) the small number of completed projects for some technology, and (c) the proprietary nature of some of the existing data which belongs to oil companies.

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[50] As denoted by the EPA.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

This section takes the technology-wide approach to impact assessment. However, as described above, this requires analysis of case studies especially for tasks (A), (B) and (C).[51] This section is organized according to the analytical tasks laid out in Figure 35.

A. Examine nine EOR/EGR technologies for groundwater concerns--

All enhanced recovery technologies involved potential groundwater concerns. Those technologies that require injection of chemicals into the reservoir or fracturing of formations hold the most potential for contamination. In situ combustion is also of particular concern because of the range of chemicals that are formed during the subsurface combustion process. Figures 20 to 25 depict the specific pollutant problems of each technology. Table 29 summarizes the types of pollutant problems which may occur.

In addition to the generic concerns, there are various environmental/institutional situations that may enhance pollutant risks. These must be looked at on a site-specific basis or in a technology-wide assessment and could be looked at in terms of probability of occurrence of the various situations. Insufficient information is available to make reliable determinations of such probabilities at this time. The types of situations of concern include:

1. EOR programs taking place in old fields in which unmapped abandoned wells exist. These old wells are in some cases imperfectly sealed and may lead to communication with freshwater aquifers.

2. EOR programs making use of old fields in which old wells are not all reworked or recapped. Cracks in cement or casings as a result of corrosion, age or both, may allow communication with freshwater aquifers. Proposed underground injection regulations would require reworkings within 1/4 mile of all EOR activities.

3. Freshwater aquifers located just above or below the producing formation. This would greatly increase the opportunity for contamination over the most common situation in which aquifers are far removed from producing layers.

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[51] We are particularly grateful to the San Francisco DOE office and to Shell for access to some unpublished recent project data which has allowed the preparation of some examples.

TABLE 29. SUMMARY OF LEVELS OF RISK ANTICIPATED FROM VARIOUS ACTIVITIES CARRIED OUT DURING ENHANCED RECOVERY PROGRAMS. THESE ARE ERCO ESTIMATES BASED UPON AVAILABLE EVIDENCE.

	ACTIVITIES CAUSING GROUNDWATER CONTAMINATION	Injection of chemicals	In Situ formation of pollutants	Cause subsurface structural changes (new pollutant routes)	Disposal of solid wastes with hazardous leachate	Summary of potential for groundwater problems
ENHANCED RECOVERY PROCESSES	Steam	-	+	-	+	Low
	In Situ Combustion	-	*	-	-	Medium
	Polymer	*	-	+	-	High
	Polymer/ micellar	*	-	+	-	High
	Alkaline	*	*	+	-	High
	CO_2	+	-	+	-	Low
	Hydraulic fracturing	+	-	++	+	Medium
	Explosive fracturing	-	-	++	-	Medium
	Directional drilling	-	-	-	-	Low

LEGEND:

- Negligible risk.

+ Potential for occasional pollutant events.

* Significant potential for regular occurrence of pollutant events if no control measures are taken.

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EPA-287 (Cin.)
(4-76)

4. EOR programs taking place in areas that have undergone significant subsidence. In such areas the subsidence events may have resulted in fracturing or other structural alterations allowing transport of pollutants.

5. High seismic activity in region of project. The producing reservoir will become a repository for brines containing a variety of injected chemicals. These hazardous wastes may escape the oil formation following any seismic events.

6. Fresh water aquifers located below disposal ponds for drilling muds and hydraulic fracturing fluids. In these situations, leachate contamination may occur.

B. Identify Possible Pollutants for Each Technology--

There are a large number of chemicals that can be used in the enhanced recovery of oil and gas. In many cases the specific formulations are not publically known. New enhanced recovery processes are under development, thus ensuring that the list of chemicals will grow. In general, the major types of chemicals include:

(a) Polymers, including polyacrylamides and polysaccharides

(b) Surfactants, mainly petroleum sulfonates

(c) Alcohols

(d) Alkalis/caustics

(e) Corrosion control agents

(f) Bactericides

(g) Cross-linking polymers

(h) Drilling muds (that contain combinations of the above chemicals combined with others)

Table 30 summarizes the types of chemicals that are required for the various EOR processes. Table A-1 in Appendix A contains lists of chemicals that may be potentially used in the process. Table A-2 lists chemicals currently marketed for EOR applications.

C. Determine Typical Volumes Used in Each Type of Project--

In order to estimate the magnitude of the environmental hazards associated with enhanced oil and gas recovery activities, estimates of the amounts and concentrations of chemicals used in typical projects are necessary. Such estimates allow the use of the comprehensive tables included in Appendix A.

EPA-287 (Cin.)
(4-76)

TABLE 30. POTENTIAL GROUNDWATER POLLUTANTS ASSOCIATED WITH EACH ENHANCED RECOVERY PROCESS

	Chemicals								
Process	Poly-mers	Sur-fact-ants	Alco-hols	Caustic	Corro-sion Control	Bac-teri-cides	Cross-Linking Polymers	Drilling Muds	Pollutants Formed In Situ
EOR									
Steam					x			x	
In situ					x			x	x
Polymer	x				x	x	x	x	
Polymer/micellar	x	x	x		x	x	x	x	
Alkaline				x	x		x	x	x
CO_2					x		x	x	
EGR									
Hydraulic	x						x	x	
Chemical explosive								x	
Directional drilling								x	

EPA-287 (Cin.)
(4-76)

At present no standard values exist that can be used to represent chemical usage for typical projects. Many of the processes are in a developmental stage. Operators have differing beliefs regarding how much polymer should be injected per unit pore volume. In many cases the data presented here are based on a small number of projects or on projects that are already outdated in their scale of applcation of the technology.

Volumes of chemicals used--

1. Summary-- Some estimates of the amounts of chemicals being used for various types of projects are given in Table 31. Problems with using such estimates include variability in the size of potential projects, different engineering views as to suitable injection water volume pore volume ratios, and the small sample size from which these estimates are taken.

2. Micellar/polymer chemicals--Micellar flooding projects require significant quantities of various chemicals. This will require the expansion of production capabilities by the chemical manufacturing industry if the technology is commercially developed even at a moderate rate. Schumacher (1978) estimates that five to ten pounds of chemicals will be required per barrel of oil produced.

3. Miscellaneous chemicals--Small volumes of drilling muds, bactericides, and corrosion control, acidizing and completion fluids are used in various EOR projects. There has been little information assembled regarding the composition, characteristics, and detrimental effects of such substances. There also has been no estimation of miscellaneous chemicals used in association with EOR projects.

4. Typical chemical concentrations--Various concentrations and combinations of chemicals are in chemical EOR floods and the design of the chemical slug is tailored to site-specific circumstances. For this reason it is very difficult to typify the exact chemicals used and their concentrations. Table 32 summarizes typical concentration ranges and presents typical chemical volume prevents used in micellar slugs. In polymer or improved waterflooding projects, polymer concentrations from 500 to 1,500 are typically used. In the case study of the micellar/polymer flood, the concentrations of slug components were calculated from the list of the components. Percentages of the total volumes of each phase are listed in Table 33.

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EPA-287 (Cin.)
(4-76)

TABLE 31. AMOUNTS OF CHEMICALS INJECTED FOR TYPICAL PROJECTS

Process	Chemical	Amount (lb)		Number of Projects Evaluated
		Mean	Range	
Polymer to 1970	Polyacrilamides	9,200	1,000-80,000	56[a]
Polymer 1970-Present	Polyacrilamides	126,000	70,000-168,000	4[b]
Polymer Commercial	Polyacrilamides	6,000,000	--	1 estimate[b]
Alkaline	NaOH	33,000 bbl	5.78×10^5 lb	1[c] (calculated with water lbs/cu ft as density)
Polymer/ Micellar	Sulfonates	5,350 bbl	1.87×10^6 lb	1[d]
	Alcohols	5,270 bbl	1.85×10^6 lb	1[d]
	Polysaccharide	581,000 bbl	2.03×10^6 lb	1[d]

[a] Agnew, 1972.

[b] Chang, 1978.

[c] Unpublished data, Shell/DOE Coalinga Project.

[d] Raimondi et al., 1977.

EPA-287 (Cin.)
(4-76)

TABLE 32. TYPICAL CONCENTRATIONS OF INJECTED CHEMICALS

Process	Chemical	Concentration Range
Polymer	Polymer	250-1,500 ppm[a]
Alkaline	NaOH	50,000 ppm[b]
Micellar/ Polymer	See Table 33	

[a] Chang, 1978.
[b] Raimondi et al., 1977.

Case study--In order to develop an estimate of the typical volumes and concentrations of chemicals used for an EOR project, a case study of the Shell Oil Company's cost-sharing project with the DOE was made. Shell Oil made certain data available so that calculations of the total chemical volumes and concentrations could be made. (Note: this project is of pilot scale and thus the final adjustment for calculating typical volumes and concentration is a scaling of the values for the pilot project up to a full, commercial scale operation. The following is the methodology used to determine the volumes of chemicals used.)

1. Estimate of typical chemical volumes used--
Step 1: List the components and the percent of the total amount for each slug fraction planned for the project, that is,for preflush, surfactant, polymer, and water fractions.

For the Coalinga case study, Step 1 was done from information provided by the project manager. A two-stage preflush used a variety of salts and as much water as the polymer and micellar slugs combined. The micellar slug contained large amounts of sulfonate, 2-butyl alcohol and water, with lesser amounts of another alcohol, NaCl and polysaccharides.

Step 2: From these slug designs, and the project number of barrels of slug, determine the total volume of each chemical to be used throughout the entire project.

For the case study, the slugs' total volumes and the slug fraction for each component made volume calculation possible for each chemical, and these

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 33. TERTIARY OIL RECOVERY - SOME TYPICAL MICROEMULSION COMPOSITIONS[a,b]

Constituent	Volume Percent Low Water[c] Oil External	High Water[d] Oil External	High Water Water External	Low Water[c] Water External
Surfactant	6-10	3-6	3-5	6-12
Cosurfactant	2-4	0.01-20	0.01-20	3-25
Hydrocarbon	30-80	4-40	2-50	20-60
Electrolyte	0.001-5[e]	0.001-4[e]	0.001-4[e]	3-5[e]
Water	5-55	55-80	30-95	25-40

[a] W.B. Bleakely, Oil and Gas Journal 69(48) (1971):50.

[b] Private communication, Union Oil of California, January 13, 1976.

[c] A "low water" emulsion slug is composed of less than approximately 50 percent water. Some operators believe that such slugs are not economically feasible.

[d] A "high water" emulsion slug is composed of more than approximately 50 percent water.

[e] Equivalent weight.

calculated volumes used in each phase of the flood are displayed in Table 34. The total volumes of each chemical used for the entire project are presented in the subsequent Table 35.

Step 3: In terms of expected oil produced, scale the estimated total volumes of chemicals up to a full-sized project. This way the amount of each chemical to be used is estimated for future full-sized projects.

For the case study, the predicted oil in place for a full-scale project in the studied field is 10^2 times that of the pilot project. If oil recovery efficiency is assumed to be constant over the field, the oil recovered by micellar polymer flooding would be 11,200,000 bbl instead of the 113, 600 to be expected for the pilot flood. The volumes of each chemical used estimated to increase on a linear scale with oil recovery would be two orders of magnitude bigger than those used for the pilot project. Table 36 illustrates what the full-scale project chemical use volumes would be.

2. Estimate of typical concentrations--Table 37 illustrates the injection concentrations for the Coalinga project.

D. Determine number and size of EOR/EGR operations--

Enhanced oil recovery activities have increased steadily in the United States over the last decade. Current energy demands and oil prices put enhanced oil recovery in a growing position among the various energy sources available to the United States. Several of the enhanced recovery processes are already technologically proven. Of these, thermal and CO_2 recovery processes are economically feasible and polymer flooding is becoming economically feasible as oil prices rise. The technical problems remaining with the polymer, surfactant/polymer, and alkaline processes can be expected to be solved over the next five years. Most current projects are at a demonstration or testing scale, on the order of tens or hundreds of acres, whereas most commercial scale projects will cover an area of several thousand acres. For example, the Exxon commercial scale West Yellow Creek Polymer Project covers 4,800 acres.

E. Determine cumulative volumes of each chemical injected--

Estimates of cumulative volumes follow directly from projections of the level of EOR activity (section D above and section F below) and estimates of volumes used per barrel of oil produced (section C above). Table 38 summarizes estimates of cumulative volumes which will be injected.

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EPA-287 (Cin.)
(4-76)

TABLE 34. CASE STUDY: COALINGA PROJECT CHEMICAL VOLUMES USED IN MICELLAR/POLYMER FLOOD

	Slug Components	Volume (bbl)
Preflush		
Stage 1		
	NaCl	4,942
	(H_2O)	(348,058)
Stage 2		
	NaCl	10,237
	CaCl	353
	MgCl	318
	(H_2O)	(342,057)
Micellar Slug		
	Sulfonate	5,350
	Alcohol C12-C15 ethoxysulfate	1,140
	2-butyl alcohol	4,130
	Polysaccharide	90
	NaCl	700
	(H_2O)	(95,000)
	Polymer slug	411
	Polysaccharide	581,130
	(H_2)	

TABLE 35. CASE STUDY: COALINGA PROJECT, TOTAL VOLUMES OF CHEMICALS USED[a]

NaCl (solution)	15,879
CaCl	353
MgCl	318
Sulfonate	5,350
$Alcohol_1$	1,140
$Alcohol_1$	4,130
Polysaccharide	581,220
Total bbl chemicals injected in 1,366,245 bbl H_2O (total water injected)	608,490

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EPA-287 (Cin.)
(4-76)

TABLE 36. CHEMICAL VOLUMES FOR LARGE-SCALE MICELLAR/POLYMER PROJECT (extrapolated from case study)

NaCl	1,587,900 bbl
CaCl	35,300 bbl
MgCl	31,800 bbl
Sulfonate	535,000 bbl
Alcohol[1]	114,000 bbl
Alcohol[2]	413,000 bbl
Polysaccharide	50,122,000 bbl

TABLE 37. CASE STUDY: COALINGA PROJECT, TYPICAL CONCENTRATIONS USED IN MICELLAR FLOODING (case study)

Flooding Stage	Volume Percent Of Slug	Chemical Concentration (ppm)
Preflush		
Stage 1		
NaCl	1.4	14,199
Stage 2		
NaCl	2.9	29,000
CaCl	0.1	1,000
MgCl	0.09	900
Micellar slug		
Sulfonate	5.35	53,500
Alcohol C_{12}-C_{15} ethoxysulfate	1.14	11,400
2 butyl alcohol	4.13	41,300
Polysaccharide	0.09	900
NaCl	0.7	7,000
Polymer slug		
Polysaccharide	0.07	700

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3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 38. RATES OF INJECTION FOR THREE CLASSES OF CHEMICALS USED BY ENHANCED RECOVERY OPERATIONS

Chemical	Technology Used	Estimated[a] Usage Rate (lb/barrel)	Oil Price ($)	Estimated Use[b] (10^6 lb/year) 1980	1985	1990	1995
Polymer[c]	Surfactant	1	15	--	43	131	146
	polymer		20	--	80	332	401
	flooding		25	--	80	387	529
Sulfonates	Surfactant	7-15 (use	15	--	401	1,204	1,405
	flooding	11 lb/bbl	20	--	803	3,413	4,215
		for calculation)	25	--	803	4,015	5,361
Alcohols	Surfactant	2-8 (use	15	--	182.5	547.5	638.1
	flooding	5 lb/bbl	20	--	365	1,551	1,916
		for calculation)	25	--	365	1,825	2,555

[a] Braxton et al., 1976.

[b] As a function of oil price and EOR production.

[c] Includes polyacrylamide and polysaccharide.

TYPING GUIDE SHEET
EPA-287 (Cin.)
(4-76)

F. Extrapolate typical EOR production levels to a widespread commercial scale--

Projection of future EOR activities involves a variety of assumptions regarding oil prices, technological developments, chemical supply, and oil in place. A review of existing projects has been developed in Section Three. The projections presented here mainly follow NPC (1976) figures with modifications based on ERCO opinions regarding the direction of the technology.

Ultimate potential recovery of oil by enhanced methods--Subsequent to primary and secondary recovery, nearly 300 billion barrels of oil will remain in known reservoirs in the United States. Over 80 percent of this oil is located in reservoirs that are suited to enhanced recovery operations. Potentially, 29 billion additional barrels of oil could be recovered at $30 per barrel if enhanced techniques were utilized.

Employment of enhanced recovery techniques is highly dependent on the characteristics of the oil and the reservoir containing it. Table 39 summarizes the major parameters that are usually initially considered in the selection of an enhanced recovery process. A review of U.S. reservoir characteristics has permitted their classification by the enhanced recovery method to which they are most suited (ERCO, 1979). Table 40 contains the current best estimates of quantity of oil in place as a function of the enhanced recovery technology that would be most able to extract it. Further, estimates of the total amount of oil that could be extracted at prices ranging from $15 to $30 per barrel are given.

Predicted production levels--Table 41 translates the estimates of ultimate daily production for each technology into daily rates for the period 1980 to 1995. It is important to note that carbon dioxide miscible flooding and surfactant (micellar-polymer) flooding are the technologies most sensitive to price changes over the next ten to fifteen years, while other technologies are relatively price insensitive when one looks at recovery rates.

Large volumes of specialty chemicals will be required for enhanced recovery operations. Current projections indicate that demand will significantly exceed supply by 1985. While chemical usage and oil recovery figures will be highly specific to each individual oil field in which enhanced techniques are attempted, it is possible to assemble reasonably reliable estimates of demand for chemicals for these operations. Chemical classes and estimated availablity and usage rates are summarized in Table 41. A matrix of demand for chemical and the (constant) dollar value of the market that they represent

TABLE 39. SCREENING CRITERIA FOR SELECTION OF EOR CANDIDATES[a]

Screening Parameters	Units	Chemical Flooding Processes: Surfactant	Chemical Flooding Processes: Polymer	Chemical Flooding Processes: Alkaline	Miscible Processes: Carbon Dioxide	Thermal Processes: Steam	Thermal Processes: In Situ Combustion
Oil Gravity	°API	≥25	-	≤35	≥27	≤25	≤25
Oil Viscosity (μ)	cp	≤30[b]	≤200	≤200	≤10	≥20	≥20
Depth (D)	feet	-[b]	-	-	>2,300	>200<5000	>5,000
Zone Thickness (h)	feet	-	-	-	-	>20	>10
Temperature	°F	≤250	≤200	≤200	<250	-	-
Permeability, Average ($\bar{K}$)	md	≥20[b]	≥20	≥20	-	-	
Transmissibility (Kh/μ)	md-ft/cp	-	-	-	-	100	20
Salinity of formation brine (TDS)	ppm	≤200,000	-	-	-	-	-
Minimum oil saturation at start of process							
In water-swept zones (S_{orw})	fraction	≥0.20	-	-	-	-	-
Mobile (S_{or}-S_{orw})	fraction	-	≥0.10				
Minimum oil content at start of process (S_{or})	B/AF	-	-	-	-	>500	>500
Rock type	-	Sandstone	-	Sandstone	Sandstone or Carbonate	Sandstone or Carbonate	Sandstone
Other	-	c	c	c	c	c	c

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[a] National Petroleum Council (1976).

[b] Used to estimate required well spacing for given project life.

[c] Other criteria including geological data were also considered. The specific content used depended upon the process. In general, reservoirs with continuous and uniform strata were ranked higher than were heterogeneous reservoirs with extensive faulting, discontinuous lens-type deposits, fractures, etc. Similarly, reservoirs with extensive underlying aquifers or overlying gas caps were ranked lower or excluded as EOR candidates in view of the decreased likelihood of a successful EOR project.

TABLE 40. SUMMARY OF UNITED STATES OIL IN PLACE (BILLIONS OF BARRELS) RECOVERABLE BY DIFFERENT ENHANCED METHODS[a,b]

	Surfac-tant	Polymer	Alkaline	CO^{2} Miscible Flood	Steam Drive	In-Situ Combustion
Oil in place (10^9)	51.762	8.382	6.824	118.761	44.802	16.100
Total ultimately recoverable (10^9) at:						
$15/barrel	2	0.480	0.380	5.200	3.000	1.800
$20/barrel	6	0.480	0.380	6.200	4.700	2.150
$25/barrel	8	0.480	0.380	7.300	5.250	2.220
$30/barrel	9	0.520	0.410	11.000	6.000	2.300

[a] This table breaks down the total oil in place by enhanced recovery technology. Reservoirs were evaluated on the basis of nine screening criteria for EOR suitability. The total oil in place in the United States is estimated at 298 billion barrels. Of that, 52 billion barrels are unsuitable for existing EOR known on the basis of the screening criteria.

[b] ERCO, 1979.

TABLE 41. POTENTIAL DAILY INCREMENTAL PRODUCTION RATE DUE TO CHEMICALLY ENHANCED TECHNIQUES - SUMMARY FOR UNITED STATES[a,b]

Technology	Year	Oil Price ($/Barrel)[c]	Production Rate (Barrels/Day)
Surfactant flooding	1980	15	-[d]
		20	-
		25	-
	1985	15	100,000
		20	200,000
		25	200,000
		30	200,000
	1990	15	300,000
		20	850,000
		25	1,000,000
		30	1,200,000
	1995	15	350,000
		20	850,000
		25	1,000,000
		30	1,200,000
Polymer flooding	1980	15	-[d]
		20	-
		25	-
		30	-
	1985	15	18,000
		20	18,000
		25	18,000
		30	18,000

---

[a] ERCO, 1979.

[b] This table indicates projected levels of EOR production by technology through 1995. Four crude oil price scenarios are used. These projections are based on National Petroleum Council (NPC) data and on ERCO analysis.

[c] 1978 $.

[d] Surfactant/polymer, polymer, and CO_2 not expected to be commercial by 1980.

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TABLE 41. (CONT.)

Technology	Year	Oil Price ($/Barrel)[c]	Production Rate (Barrels/Day)
Polymer flooding (cont.)	1990	15	60,000
		20	60,000
		25	60,000
		30	60,000
	1995	15	50,000[e]
		20	50,000
		25	50,000
		30	50,000
Steam flooding	1980	15	300,000
		20	450,000
		25	450,000
		30	450,000
	1985	15	490,000
		20	700,000
		25	700,000
		30	700,000
	1990	15	460,000[f]
		20	720,000
		25	770,000
		30	800,000
	1995	15	350,000[g]
		20	450,000
		25	520,000
		30	580,000
In situ combustion	1980	15	150,000
		20	180,000
		25	200,000
		30	220,000

[e] Polymer and alkaline recovery decline by 1995 due to the ultimate limited potential of the technology.

[f] Steamflood yields reduced by 1990 at low prices as suitable reservoirs are expended and the major remaining resource requires expensive ancillary additives.

[g] Steamflood and in situ combustion yield significantly reduced by 1995 due to the ultimate limited potential yield of the technology.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 41. (CONT.)

Technology	Year	Oil Price ($/Barrel)^c	Production Rate (Barrels/Day)
In-situ combustion (cont.)	1985	15	100,000
		20	130,000
		25	150,000
		30	170,000
	1990	15	320,000
		20	370,000
		25	380,000
		30	400,000
	1995	15	300,000[h]
		20	350,000
		25	360,000
		30	380,000
CO_2 flooding	1980	15	--[i]
		20	--
		25	--
		30	--
	1985	15	100,000
		20	280,000
		25	450,000
		30	600,000
	1990	15	270,000
		20	430,000
		25	670,000
		30	800,000
	1995	15	700,000
		20	1,070,000
		25	1,230,000
		30	1,415,000

---

[h] Surfactant/polymer, polymer, and CO_2 not expected to be commercial by 1980.

[i] Steamflood and in situ combustion yield significantly reduced by 1995 due to the ultimate limited potential yield of the technology.

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EPA-287 (Cin.)
(4-76)

TABLE 41. (CONT.)

Technology	Year	Oil Price ($/Barrel)[c]	Production Rate (Barrels/Day)
Alkaline flooding	1980	15	22,000
		20	22,000
		25	22,000
		30	22,000
	1985	15	65,000
		20	65,000
		25	65,000
		30	65,000
	1990	15	120,000
		20	120,000
		25	120,000
		30	120,000
	1995	15	30,000[j]
		20	30,000
		25	30,000
		30	30,000
Total	1980	15	337,000
		20	490,000
		25	492,000
		30	494,000
	1985	15	873,000
		20	1,113,000
		25	1,133,000
		30	1,153,000
	1990	15	1,260,000
		20	2,120,000
		25	2,330,000
		30	2,580,000
	1995	15	1,030,000[k]
		20	1,930,000
		25	2,360,000
		30	2,740,000

[j] Polymer and alkaline recovery decline by 1995 due to the ultimate limited potential of the technology.

[k] Total production begins to decline except for the highest price scenarios by 1995 as suitable reservoirs are used up.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

are given in Table 42. Chemical demand will be primarily determined by the expected production of oil, which is in turn determined by the then current prices. The potential market value of these chemicals will then be a function of (1) chemical supply and demand, and (2) oil price, since many of these chemicals are petroleum-based and/or require large amounts of energy in their manufacture.

In the most optimistic case, the market for chemicals will grow to a total constant dollar value of 5,498 million dollars per year in 1995. An extremely pessimistic view has the market growing to only 1032.8 million dollars per year in 1995. These would be expected to be peak values, as projections of daily production from enhanced recovery operations all show a decline after 1995.

G. Predictions for each chemical, for each region--

The projections developed in steps [E] and [F] of the analysis (above) provide a generalized picture of the level of enhanced recovery production that will occur and the resulting use of chemicals. More information would be desirable to allow a ranking of the importance of various chemicals as potential pollutants. The type of information needed to determine which sorts of chemicals are going to be used in specific areas include data regarding connate water concentration, reservoir geology (permeability, depth, and thickness), temperature, oil viscosity, oil gravity, oil saturation. These data can then be used to predict types of chemicals that will be used in certain regions. The DOE is in the process of developing a comprehensive data base which will satisfy these information needs (Gary Operating Co., 1979). Tables 43 and 44 display available information on connate waters. Until the new DOE data base is online, this analytical step cannot be performed.

H. Rank possible pollutants by predicted volumes and concentration used--

For the formulation of an initial understanding of which chemicals should be given the most attention in the study of fates and effects, a ranking of EOR/EGR chemicals in terms of volume concentration, and thus of importance as essential pollutants, is essential. This cannot be done properly until steps [C] and [G] are fully developed.

I. Develop toxicity data, degradation product information and hazardous ratings--

1. Toxicity/carcinogenicity data--Several hundred chemical formulations are used from time to time as part of the nine enhanced recovery technologies. The task of assembling the required toxicity and chemical activity data is formidable, particularly since (1) many of the chemicals used are patented and chemical fabricators will not release the necessary data

EPA-287 (Cin.)
(4-76)

TABLE 42. RATES OF INJECTION FOR THREE CLASSES OF CHEMICALS USED BY ENHANCED RECOVERY OPERATIONS

Chemical	Technology Used	Estimated[a] Usage Rate (lb/barrel)	Oil Price ($)	Estimated Use[b] (10^6 lb/year) 1980	1985	1990	1995
Polymer[c]	Surfactant polymer flooding	1	15	--	43	131	146
			20	--	80	332	401
			25	--	80	387	529
Sulfonates	Surfactant flooding	7-15 (use 11 lb/bbl for calculation)	15	--	401	1,204	1,405
			20	--	803	3,413	4,215
			25	--	803	4,015	5,361
Alcohols	Surfactant flooding	2-8 (use 5 lb/bbl for calculation)	15	--	182.5	547.5	638.1
			20	--	365	1,551	1,916
			25	--	365	1,825	2,555

[a] Braxton et al., 1976.

[b] As a function of oil price and EOR production.

[c] Includes polyacrylamide and polysaccharide.

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EPA-287 (Cin.)
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TABLE 43. CONCENTRATION OF IONS IN CONNATE WATERS WITH QUANTITIES OF OIL IN PLACE (in millions of barrels) SUMMARY FOR UNITED STATES[a]

This table breaks down the United States reserves accessible to enhanced recovery according to chemical composition. Breakdowns are presented for three important chemical indices. Data are based on a sample of 400 wells distributed throughout the United States.

	Ranges of Concentrations in Connate Waters										
	Divalent Ions (Mg^{++}, Ca^{++})										
Connate water concentration (ppm)	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1,000	over 1,000
Reserves in place (in million bbls of oil)	170,000	43,000	22,000	15,000	9,200	7,000	5,300	3,800	3,400	2,400	1,800
	Sodium Chloride (Na^{++})										
Connate water concentration (ppm)	0-500	500-1,000	1,000-2,000	1,500 2,000	2,000 2,500	2,500 3,000	3,000 3,500	3,500 4,000	4,000 4,500	4,500 5,000	over 5,000
Reserves in place (in million bbls of oil)	80,000	50,000	32,000	22,000	17,000	13,000	11,000	8,300	6,000	5,700	5,400
	Total Dissolved Solids (TDS)										
Connate water concentration (ppm)	0-50,000	50,000-100,000	100,000-150,000	over 150,000							
Reserves in place (in million bbls of oil)	290,000	3,500	360	720							

[a] ERCO, 1979.

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TABLE 44. TYPICAL CONNATE WATER COMPOSITIONS

	TDS (ppm)	Divalent Ions (ppm)
Colorado		
Rangeley	108,053	4,077
Montana	5,440 - 8,800	--
Cut Bank		
New Mexico		
Hobbs	21,566	590 - 10,000
Vacuum	27,121 - 219,649	1,710 - 14,716
Wyoming		
Oregon Basin	7,403	730
Salt Creek	3,969 - 12,384	22 - 103

[a] ERCO, 1979.

and (2) the list of chemicals being used for enhanced recovery is continuously evolving as new approaches are developed.

Assembled here are the available data regarding acute toxicity and mutagenicity/carcinogenicity. Information on toxicity was assembled based on a search of the toxicology literature employing chemical names and formulas where available. Information on carcinogenicity/mutagenicity is based on two sources which summarize results of Ames assay-type screening tests through 1976 (McCann et al., 1975; Sugimura et al., 1976). Tables 45 and 46 summarize the information which has been assembled. Tables 47 through 54 present the available data.

In evaluating and using the information presented here there are several important factors that must be taken into consideration. First, in cases where the enhanced recovery technology uses a broad group of chemicals, such as amides, only representative samples from the literature have been included in these data tables. It was impossible to cover such broad groups completely in the context of this report. Second, the summary tables should be used with great care. The ranking

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TABLE 45. SUMMARY OF ACUTE TOXICITY RATING DATA[a]

	Acute Toxicity Rating[b]				Qualifications
	H	M	L	U	
Formaldehyde			x		TLm96: 100-10 ppm, orl-hmn TC_{LO} = 13.8 mg/kg
Alkyl phosphates				x	
Acetate salts of coco amines				x	
Alkyl amines				x	
Alkyl dimethyl ammonium chloride				x	
Acetate salts of tallow diamines				x	
Sodium silicate				x	orl-rat LD_{50} = 1300-1600 mg/kg
Calcium sulfate				x	
Hydroxides				x	

Phenols	x			x	TLm96: 100-10 ppm;
					orl-ham TD_{LO} = 14 mg/kg;
					orl-rat LD_{50} = 414 mg/kg;
					orl-mus LD_{50} = 300 mg/kg;
					orl-rbt LD_{LO} = 420 mg/kg

Polyoxyethylene				x	
Alkyl osyl sulfonate				x	
Fusel oil				x	
Isopentanol				x	

[a] National Institute for Occupational Safety and Health, 1977.

[b] See Key to Table 45. H = high acute toxicity; M = medium acute toxicity; L = low acute toxicity; U = unknown acute toxicity.

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EPA-287 (Cin.)
(4-76)

TABLE 45. (CONT.)

	Acute Toxicity Rating[b]				
	H	M	L	U	Qualifications
Ethanol			x		TLm96: >1,000 ppm; orl-hm LD_{LO} = 6,000 mg/kg
			x		orl-rat LD_{50} = 2,460 mg/kg; orl-rat TD_{LO} = 29,000 mg/kg orl-rbt LD_{LO} = 3,750 mg/kg
n-Butanol			x		TLm96: <1,000 ppm; orl-rat LD_{50} = 790 mg/kg orl-mus LD_{LO} = 3,000 mg/kg orl-rbt LD_{LO} = 4,250 mg/kg
Cyclohexanol			x		TLm96: 100-10 ppm; orl-rbt LD_{50} = 2,060 mg/kg; orl-dog LD_{LO} = 1,300 mg/kg
10hexanol		x			orl-rat LD_{50} = 720 mg/kg orl-must LD_{50} = 1,950 mg/kg
1-octanol			x		TLm96: 100-10 ppm; orl-must LD_{50} = 1,790 mg/kg
Isopropanol			x		TLm96: 1,000-100 ppm; orl-hmn LD_{LO} = 2,371 mg/kg

Cresol		x			orl-rat LD_{50} = 242 mg/kg;
					orl-mus LD_{50} = 828 mg/kg;
					orl-rbt LD_{LO} = 1,400 mg/kg;

(continued)

TABLE 45. (CONT.)

	Acute Toxicity Rating[b]				Qualifications
	H	M	L	U	
Ketones			x		
Polyacrylamide			x		
Polysaccharide polymers			x		
Amines			x		
Carboxymethylcellulose				x	ivn-mus LD_{50} = 47 mg/kg
Dextrans				x	
Deoxyribonucleic acid				x	
Glycerin			x		TLm96: >1,000 ppm orl-mus LD_{50} = 470 mg/kg; orl-gpg = 7,750 mg/kg
Sulfates				x	
Sulfonates				x	
Benzene			x		TLm96: 100-10 ppm; orl-mus LD_{50} = 4,700 mg/kg; orl-dog LD_{LO} = 2,000 mg/kg
Toluene				x	
Crude oil fractions				x	

Kerosene	x				orl-rat LD_{LO} = 28 mg/kg;
					orl-rbt LD_{50} = 28 mg/kg;
					orl-gpg LD_{50} = 20 mg/kg;
					orl-hmn LD_{LO} = 500 mg/kg

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EPA-287 (Cin.)
(4-76)

TABLE 45. (CONT.)

	Acute Toxicity Rating^b				
	H	M	L	U	Qualifications
Hydrogen peroxide				x	
Sodium hydrosulfite				x	
Guinoline				x	
Toluene				x	
Hydrazine				x	

KEY:

ivn	intravenous administration
orl	oral administration
scu	subcutaneous administration
gpg	guinea pig
hmn	human
mus	mouse
rbt	rabbit
rat	rat
TLm96	Aquatic toxicity rating is defined as the median threshold limit value during 96-hour static or continuous flow standard protocol. Indicates toxicity of substances to aquatic life.
LD	lethal dose
TD	toxic dose
LC	lethal concentration
TC	toxic concentration

Subscripts

LO	Number of subjects studied was not a significant proportion of the population, that is, lowest dose to produce an effect, but not necessarily a significant effect.
50	Calculated dose of a substance which is expected to affect 50 percent of an entire defined experimental animal population.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 46. RANKING CRITERIA FOR TABLE 45

High	TLm96	< 1 ppm$_{EPA}$
	LD$_{50}$	< 250 mg/kg orl-rat
	LD$_{50}$	< 500 mg/kg orl-mus
	LD$_{LO}$	$< 1{,}000$ mg/kg orl-rbt
Medium	TLm96	$1 < 10$ ppm$_{EPA}$
	LD$_{50}$	$250 < 1{,}000$ mg/kg orl-rat
	LD$_{50}$	$500 < 1{,}500$ mg/kg orl-mus
	LD$_{LO}$	$1{,}000 \leq 2{,}000$ mg/kg orl-rbt
Low	TLm96	$10 < 100$ ppm$_{EPA}$
	LD$_{50}$	$1{,}000 < 2{,}500$ mg/kg orl-rat
	LD$_{50}$	$1{,}500 < 3{,}000$ mg/kg orl-mus
	LD$_{50}$	$2{,}000 < 4{,}000$ mg/kg orl-rbt

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of chemicals by acute toxicity does not imply overall importance of the chemical as a pollutant in enhanced recovery. Depending on the concentration levels occurring in different injection schemes, specific rankings can be prepared that take into account existing concentrations and thus have more direct usefulness. Third, specific data here for specific chemical formulations cannot be extrapolated to any other chemicals, no matter how similar the chemical structure. No general rules have been discovered by toxicologists to allow such relationships to be inferred. Slight differences in chemical structure may cause major changes in the biological activity of the substance. Hence each chemical of potential concern will need to be tested individually.

1.a Chemical Toxicity--The current status of data on EOR chemical toxicity is presented in Tables 47 to 49. Base information concerning acute toxicity was obtained from the NIOSH Registry of Toxic Effects of Chemical Substances, 1977, and was organized into relative toxicity tables according to the testing organism: Table 47 reports rat data, 48, mussel data; 49, rabbit data; and 50 reports a ranking of acute aquatic toxicity data.

Table 50, a summary of acute chemical toxicity ranking, is presented as an example of how these data can be organized. In its present form this table is included as a preliminary

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 47. ACUTE CHEMICAL TOXICITY RATING FOR AVAILABLE LD_{50} ORL-RAT DATA, EOR CHEMICALS[a,b]

Compound	Toxicity Rating (mg/kg)
Cresol	242
1-Hexanol	720
n-Butanol	790
p-formaldehyde	800
Sodium silicate	300-1,600
Naphthalene	1,780
Isobutanol	2,460

[a] See Key to Table 45.

[b] National Institute for Occupational Safety and Health, 1977.

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TABLE 48. ACUTE CHEMICAL TOXICITY RATING FOR AVAILABLE LC_{50} ORL-MUSSEL DATA, EOR CHEMICALS[a,b]

Compound	Toxicity Rating (mg/kg)
Glycerol	470
Cresol	828
1-Octanol	1,790
1-Hexanol	1,950
Benzene	4,700

[a] See Key to Table 45.

[b] National Institute for Occupational Safety and Health, 1977.

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EPA-287 (Cin.)
(4-76)

TABLE 49. ACUTE CHEMICAL TOXICITY RATING FOR AVAILABLE LD_{50} ORL-RABBIT DATA, EOR CHEMICALS[a,b]

Compound	Toxicity Rating (mg/kg)
Cresol	1,400
Cyclohexanol	2,200
Isobutanol	3,750
n-Butanol	4,250

[a] See Key to Table 45.

[b] National Institute for Occupational Safety and Health, 1977.

TABLE 50. ACUTE TOXICITY RANKING OF DATA FOR EOR CHEMICALS[a,b]

Compound	Acute Aquatic Toxicity (ppm)
Naphthalene	10-1
Formaldehyde	100-10
Benzene	100-10
Phenol	100-10
Cyclohexanol	100-10
1-Octanol	100-10
Isopropanol	1,000-100
Glycerol	>1,000
Ethanol	>1,000
n-Butanol	>1,000

[a] See Key to Table 45.

[b] National Institute for Occupational Safety and Health, 1977.

indicator of ranking and not as a complete product. The table can be updated when more chemical substances have been assayed and new ranking criteria can be developed when a cleaner picture of EOR chemical concentrations is developed. The chemicals are ranked in categories of high, medium, low, and unknown for acute chemical toxicity and lethality according to the criteria specified in Table 46.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

1.b *Mutagenicity-carcinogenicity data for chemicals associated with micellar/polymer and improved floods: Ames assay test determinations*--Tables 51 to 54 summarize those chemicals from the tertiary oil recovery tables for which information was available with regard to mutagenicity and/or carcinogenicity. Ames assays are currently being carried out by a number of researchers, thus, the data presented in these tables can be expected to be updated and expanded. The Ames assay involves the inoculation of bacterial strains with enzymes and a known concentration of a hazardous chemical. The test provides direct data on the mutagenicity of the chemical on a particular strain at a known concentration. A body of research data developed by Bruce Ames and others has been used to support the contention that bacterial mutagenic agents are usually also human mutagenic agents, and in a significant proportion of cases also human carcinogenic agents. However, for chemicals identified as mutagenic by the Ames screen, further testing is required using mammals before any regulatory actions should be taken.

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The alkyl aryl sulfonate, ethyl *p*-toluene, sulfonate, was found to be weakly mutagenic (McCann, et al., 1975; personal communications from V. Simmon (SRI) and H. Rosencranz (New York Medical College), and is listed as being weakly carcinogenic.

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Ethylene glycol and naphthalene have been tested for mutagenicity, although their derivatives, diethylene glycol sulfonate and hexadecylnaphthalene sulfonate, have not. The former compounds have been shown to be non-mutagenic (McCann et al., 1975), and are listed as being non-carcinogenic. Lack of mutagenicity of parent compounds does not, however, indicate safety of derivatives.

2. *Chemical fate modeling*--Chemical fate modeling can be used to support a sampling program, as well as to establish the necessity of, and to aid in the design of, an effective sampling program. Chemical fate modeling is required to determine the possible level of contamination of underlying and overlying aquifers from chemicals injected in chemical EOR processes. As suggested by the different flux terms (in Figure 36), pollutants could seep into aquifers by vertical migration of chemicals and for decomposition products.

Chemical fate modeling should be done as an adjunct to most chemical flood programs in order to check the potential leakage path. The amount of leakage can be inferred from incomplete mass balances on injected chemical species. The measured breakthrough concentration profiles at the producers and the laboratory determined adsorptive and retentive parameters are inputs into such mass balances. The concentration and composition of potential pollutants can be determined from the difference between the inputs and the outputs.

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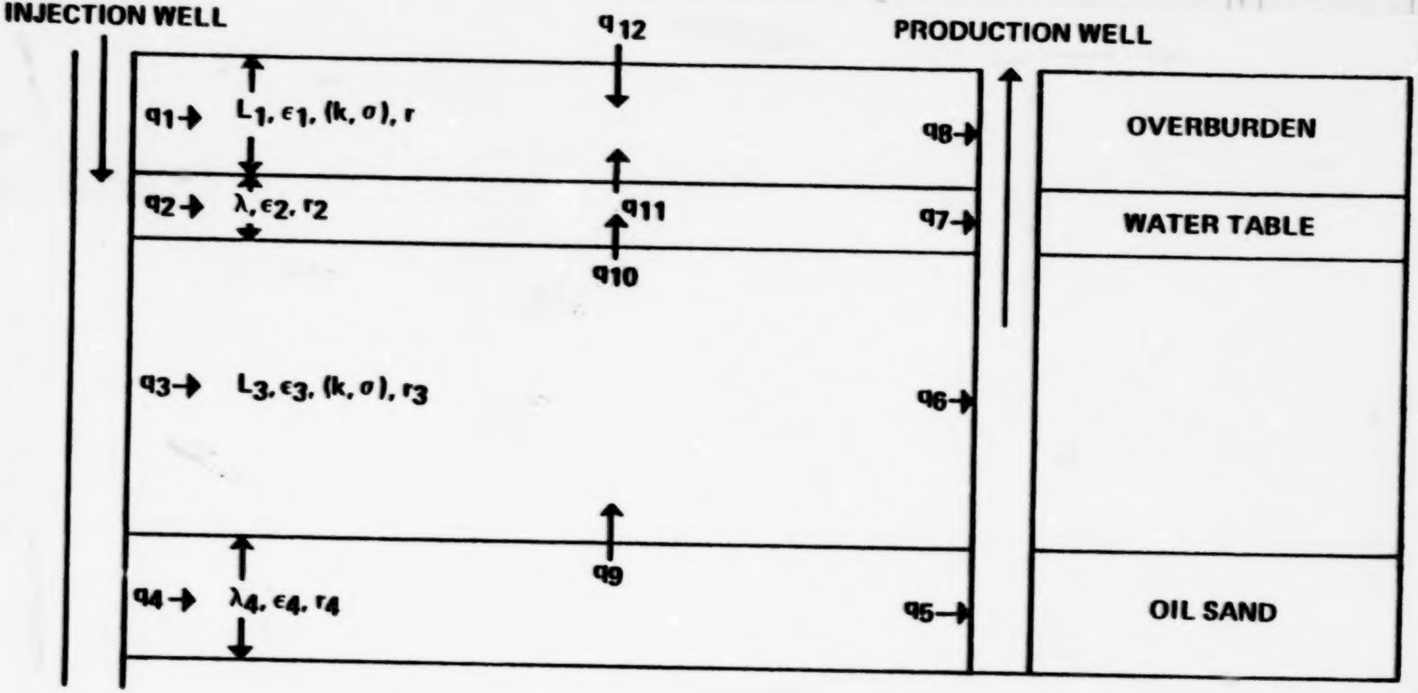
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PRODUCTION WELL
q_{12}
q_1
$L_1, \epsilon_1, (k, \sigma), r$
q_2
λ, ϵ_2, r_2
q_{11}
q_{10}
q_3
$L_3, \epsilon_3, (k, \sigma), r_3$
q_9
q_4
$\lambda_4, \epsilon_4, r_4$
q_8
q_7
q_6
q_5
OVERBURDEN
WATER TABLE
OIL SAND

Phenomena Modeled:
1. Convective transport in substructures, q
2. Inter–Structure transport, q
3. Absorption (k, T)
4. Chemical production of pollutants as a result of shear and temperature, r

Figure 36. Transport and fate modeling.

EPA-287 (Cin.)
(4-76)

TABLE 51. AMES TESTS ON CHEMICALS PROPOSED FOR USE AS COSURFACTANTS[a]

Compound	Muta- genicity	Carcino- genicity
Ethanol[b]	-	-
m-Butanol[b]	-	-
Amides[b]		
Thioacetamide	-	weakly
Acetamide	-	weakly
Cyclophosphamide	+	+
Isophosphamide	+	+
Amino compounds[c]		
4-Aminoazobenzene	+	+
o-Aminoazotoluene	+	+
4-Aminobiphenyl	+	+
p-Aminobenzoic acid ethyl ester	-	
2-Amino-4-(5-nitro-2-furyl) thiazole	+	+
Amides		
Cyclophosphamide[b]	+	+
Isophosphamide[b]	+	+
2-(2-Furyl)-3-(5-nitro-2-furyl) acrylamide[c]	+	+
3-(5-Nitro-2-furyl) acrylamide[c]	+	
Acetamide[b]	-	weakly

[a] Information was available on the following compounds. Where only broad categories were given on the table, examples of chemicals that fit into these broad chemical categories are included. Needed for further work are specific examples of the ketones that are used in EOR (or of any of the above categories) which could then be evaluated correctly on an individual basis.

[b] McCann et al.

[c] Sugimura et al.

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3/8"

EPA-287 (Cin.)
(4-76)

TABLE 52. AMES TESTS ON MATERIALS PROPOSED FOR USE AS MOBILITY BUFFERS[a]

Compound	Mutagenicity		Carcino-genicity
	S. typh.	*E. coli*	
Amines[a]			
α-naphthalene	+		+
α-naphthylamine	+		-
butylbutanolamine	-		
(most aromatic amines are mutagenic and carcinogenic)			
Dextrane[a]	-		-
(is this a dextran?)			
Carboxymethyl cellulose[a]	-	-	-

[a] Sugimura et al., 1976.

6-1/2"

TABLE 53. AMES TESTS ON HYDROCARBONS USED AS FRACTION OF MICELLAR SLUG[a]

9-1/8"

Compound	Muta-genicity	Carcino-genicity
Alkylated aryl compounds	+	+
6-Hydroxymethylbenzo(a)pyrene	+	+
3-Methylcholanthrene	+	+
4-Methylbenzanthracene	+	+
7, 12-Dimethylbenzanthracene	+	+
7, 9- or 7, 10-Dimethylbenzacridine	+	+
to name a few		
Cyclohexane	-	b
Naphthenic compounds		
Naphthalene[c]	-	-
1-Naphthol[c]	-	b

[a] McCann et al., 1975, for *S. typhimurium*.

[b] Still some question; needs more work.

[c] Fractions of crude oil contain polycyclic aromatic hydrocarbons that are carcinogenic and mutagenic.

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 54. AMES TESTS ON OTHER EOR/EGR CHEMICALS

Category	Data Available
Chemicals proposed for use as electrolytes	Some information may be available for organic salts, acids and bases, but these categories are too broad to look up Ames test determinations. Some specific examples are needed.
Chemicals proposed for use to block exchange sites in the formation	No information.
Chemicals proposed for use to initiate ignition of in-situ combustion	Although no information was available for hydrazine, McCann et al., 1975, indicate that hydrazine sulfate is carcinogenic and weakly mutagenic.
Chemicals proposed for use to increase efficiency of thermal methods	Sugimura et al., 1976, lists quinoline as being both carcinogenic and mutagenic for S. typhimurium
Chemicals used as bactericides and biocides	No information was available for anything unless butylbutanolamine is an alkyl amine, in which case it is not mutagenic for S. typhimurium (Sugimura et al., 1976).

Simple partial differential equations (PDE) would be developed to describe the vertical migration of the possible pollutants. A generalized but simple PDE would include contributions from diffusive fluxes, convective fluxes, and adsorptive and reactive losses. The reactive loss could result from a combination of chemical, electrochemical, mechanical, and thermal stress. Simplified versions of such a generalized approach will be solved analytically to determine the parametric sensitivity of these potential pollutants to vertical migration. From such a simple analysis, estimates will be made of the minimum distances of aquifers from net pay, as a function of reactive and flux terms, required to effectively stop the vertical migration of the chemicals. These parametric curves will serve as a basis for a groundwater sampling program. The interaction of the different reactive and flux terms will be made from numerical integration (4th order Runge-Kutta) of the generalized PDE.

EPA-287 (Cin.)
(4-76)

3. Case study: the Coalinga polymer demonstration project study--The Coalinga Polymer Demonstration Project is located in the northern end of the San Joaquin Valley in western central California. The project pay zone is a section within the Middle Miocene unconsolidated sands of the Temblor formation. The project area includes four 22-acre inverted five-spot patterns and a 44-acre updip area where production wells will be monitored to help evaluate the project's success. The pay zone is actually made up of ten sand zones within a 350-foot vertical interval and production from a number of those sands in each area was expected (see map, Figure 37, and summary of reservoir characteristics, Table 55).

3.a Polymer concentrations and amounts--Information on polymer concentrations in the injected "slug" is needed to evaluate environmental hazard potential from leaks. For this typical example, data are minimal. The polymer injection phase of the selected case study is planned to continue for 1.5 years. According to the first annual report a concentration of approximately 300 ppm is planned for injection into the formation (Bates, 1976). In a later progress review, Shell reported the initial polymer slug would consist of a 400-ppm polymer solution (Bates et al., 1978). Sampling observation wells are being monitored to determine the advance of the flood (Bates et al,1977). At present, there are minimal data on the polymer concentrations in these sampling observation wells.

Polymer concentrations in produced waters have been measured by Shell Oil Company (Bates et al., 1978) for the months of October and November, 1978. The concentrations of polymer measured at the producing wells ranged from 1 to 30 ppm. In order to properly utilize this data to determine environmental risks additional data are required on when and at what polymer concentrations breakthrough occurred.

The sampling data included in the Monthly Technical Reports for October and November 1978 are summarized in Tables 56 and 57.

3.b Tracer Studies--Radioactive or chemical tracers were planned to be injected into the four injection wells several times during the course of the project. These tracers include: tritium, sulfur 35, cobalt 60, and potassium iodide (Bates et al., 1977). The cobalt 60 tracer did not survive intact in the reservoir. The cobalt cyanide that was used as the injection substance for the cobalt tracer was not detected in any of the surrounding producing wells (Bates et al., 1977); the cobalt may have reacted with iron in the formation. Iodine 125 and tritiated water were subsequently injected (Bates et al., 1977). The times required for movement from injector to

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

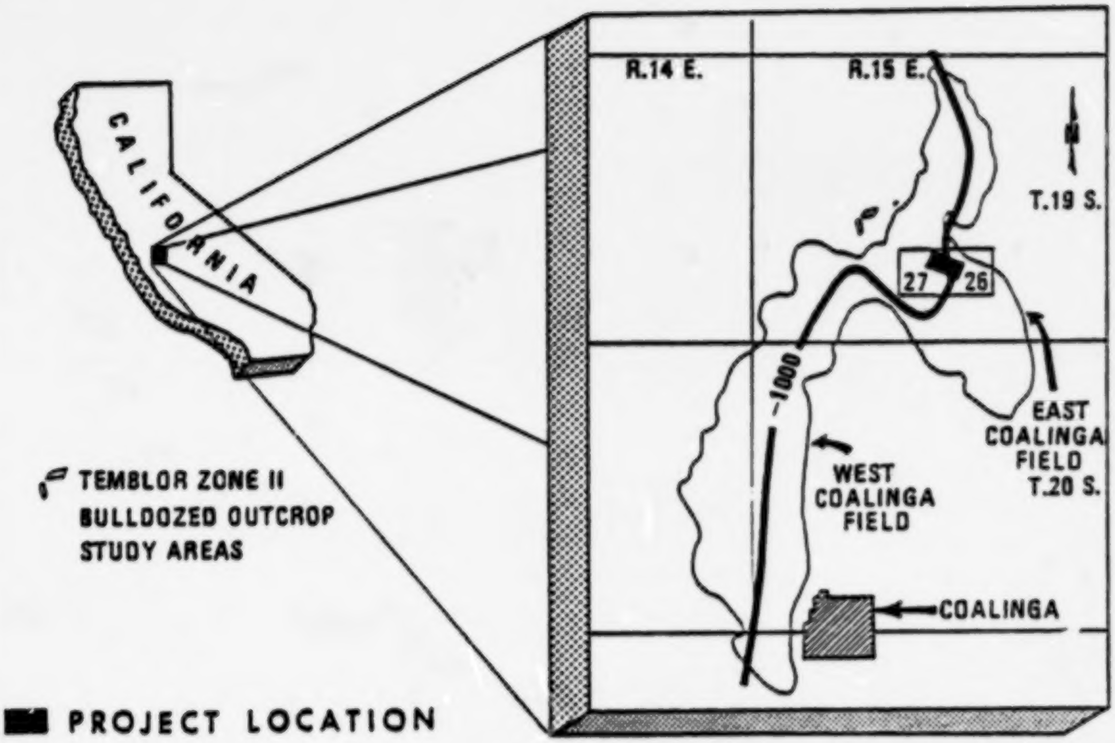
CALIFORNIA
R.14 E.
R.15 E.
N
T.19 S.
27
26
-1000
EAST COALINGA FIELD
T.20 S.
WEST COALINGA FIELD
COALINGA
TEMBLOR ZONE II BULLDOZED OUTCROP STUDY AREAS
PROJECT LOCATION

Figure 37. Case study: Coalinga Polymer Project, Coalinga Field Index map. (Baker et al. 1976).

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 55. CASE STUDY: COALINGA POLYMER PROJECT TEMBLOR ZONE II RESERVOIR PROPERTIES AND PROJECT PARAMETERS[a]

	Demonstration Project
Project area (acres)	132
Reservoir thickness (feet)	125
Number of layers	8
Injection Rate (bbl/day)	5,400
Number of injection wells	4
Porosity	0.265
Permeability (md)	50-480
Initial oil saturation (in region of no oil desaturation)	0.650
Water displacement residual oil saturation	0.235
Gravity drainage residual oil saturation	0.130
Oil gravity (°API)	21.0
Reservoir temperature (°F)	100
Oil viscosity at reservoir temperature (cp)	25.0
Water displacement mobility ratio	14.0
Current oil in place (S.T. bbl)	17,780,000
Movable oil in place (S.T. bbl)	10,295,000
Future primary oil recovery (S.T. bbl)	710,000
Polymer flood recovery (fraction of movable oil in place)	0.326
Polymer flood recovery (S.T. bbl)	2,645,000
Waterflood recovery (fraction of movable oil in place)	0.267
Waterflood recovery (S.T. bbl)	2,040,000
Polymer flood over waterflood (S.T. bbl)	605,000
	Full-scale Project
Project area (acres)	2,600
Injection rate (bbl/day)	120,000
Number of injection wells	120
Number of producing wells	200
Polymer flood recovery (S.T. bbl)	35,000,000
Waterflood recovery (S.T. bbl)	27,000,000
Polymer flood over waterflood (S.T. bbl)	8,000,000

[a]Bates et al., 1976.

TABLE 56. CASE STUDY: COALINGA POLYMER PROJECT POLYMER CONCENTRATIONS IN PRODUCED WATERS[a]

	Polymer Concentrations in Produced Waters (ppm)							
	Sampling Weeks							
Well(s)	10/1	10/9	10/15	10/22	10/29	11/5	11/12	11/19
Within 500 ft of injectors								
AA 15-8-27	14	5	3	7	1	3	6	4
BB 16-7-27	23	20	20	29	26	30	-	42
CC 285-27	17	5	-	8	4	-	-	-
DD 294-27	-	17	-	35	20	0	15	-
Far wells								
A 1-5-26	12	11	6	-	-	-	6	-
B 94-27	-	-	-	-	8	10	10	-
C 118-27	-	16	4	-	4	4	-	-
D 172-27	-	8	17	-	6	12	-	-
E 176-27	-	10	6	7	9	19	-	6
F 285-A-27	-	10	-	-	8	8	-	-

[a] Bates et al., 1978.

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 57. CASE STUDY: COALINGA POLYMER PROJECT - AVERAGE VALUES OF POLYMER CONCENTRATIONS IN PRODUCED WATERS (ppm)[a]

	Mean Polymer in ppm	
Near wells[b]		
AA	5.4	$\bar{X}$ of conc. in near wells = 17.7 ppm[c]
BB	27.1[c]	
CC	8.5[c]	$\bar{X}$ = 7.3 (over 8 weeks)
DD	21.7[c]	
		(7 months after polymer injection) (2 months after breakthrough)
Far wells[d]		
A	8.8[c]	
B	9.3[c]	
C	8.0[c]	
D	10.8[c]	
E	9.5[c]	
F	8.6[c]	
$\bar{X}$ conc. in far wells	9.2[c]	

[a] Bates et al., 1978.

[b] Wells with proximity to injector (500 ft or less).

[c] Wells greater than 500 ft from nearest injector(s).

[d] Averaged over only the weeks for which there was a value recorded.

EPA-287 (Cin.)
(4-76)

TABLE 58. CASE STUDY: COALINGA POLYMER PROJECT - SUMMARY OF INJECTION TRACER RESULTS[a]

Tracer	Tagged Chemical Form	Date Tracer Injected	Range of Dates Tracer Detected at Producer Wells
Potassium iodide	KI	8-2-76	8-15-76 to 9-19-76
Tritium (H-3)	H_2O	8-26-76	8-13-76 to 3-1-77
Cobalt 60 (Co-60)	$(Co(CN)_6)^{-3}$	8-2-76	
Iodine 125 (I-125)	KI	12-2-76	1-16-77 to 2-7-77
Sulfur-35 (S-35)	SO_4^{-2}	8-2-76	8-6-76 to 9-19-76

[a] Bates et al., 1977.

EPA-287 (Cin.)
(4-76)

producer within the five spots are listed in Table 58 (Bates et al., 1977). No wells outside the formation were monitored for tracers.

Additionally, in order to draw conclusions from these studies about dispersion of these injected chemicals the injection and production concentration and amounts are needed.

3.c Nature of Chemicals Used--A dry biopolymer, the Kelzan MF polymer, will be used with an Acrolein biocide in the Coalinga project. This biopolymer is very stable against viscosity degradation resulting from high shear and is very tolerant of the various ions which usually cause problems with polyacrylamides. At low concentrations, that is, an injection concentration of 300 ppm, the biopolymer experiences shear degradation in the presence of NaCl; however, divalent ions have little effect if the pH is maintained between 6 and 8. The biopolymer tends to form gels with borate or trivalent ions. At temperatures higher than 195°F the biopolymer oxidizes at a high rate but not when the reservoir is only 100°F and oxygen scavengers are used. This tendency, however, may produce significant degradation products if the biopolymer travels from the oxygen scavenged area (Bates, 1976).

The polysaccharide is biodegradable under both anaerobic and aerobic conditions. Adsorption is mentioned in Shell Oil Company's first annual report (Bates, 1976) as 3.2 micrograms per gram. The cation exchange capacity per unit pore volume (a measure of "formation shaliness" or clay content) was determined along open hole logging runs. These values, or an average of them, may be used in predicting retention (Bates et al., 1978). The biopolymer has no known toxic properties. The biocide is not found in the toxicological literature.

3.d Groundwater Information--During the water injection phase that began in June 1976, a total of 5,400 barrels per day was injected through four injection wells. At the time the first annual report was published this injection procedure was expected to continue for approximately 1 year. A rough estimate of water use during the water injection phase would therefore be 2 million barrels of water. In order to calculate total water use estimates for the entire project, the amount of water necessary for polymer injection (1.5 years) and the following additional water injection (approximately 8 years) should be added to the 2-million-barrel figure.

In the stratigraphic layers above the producing Temblor I zone there are two sandy formations that may contain aquifers. However, there is a formation composed of claystone with a few sands and gravels that may serve as a barrier to vertical

EPA-287 (Cin.)
(4-76)

movement of fluids above the Temblor I zone. Contamination would be permitted if it were discontinuous or drilled through in such a way that it permits migration of fluids upward and thus into other formations. Insufficient information exists to make judgments in that regard.

For the Coalinga project, it is estimated that 10 years would be required to expand the project to full scale and that during the peak period of injection 120,000 barrels per day would be injected. During the 1.5 years of the polymer injection phase, the injection will involve full water injection volumes plus about 300 bpd side stream passing through the polymer mixing facility.

The fresh water used for injection at the project is from the U.S. Bureau of Reclamation Feather River Project. The water is transported by canal to the project and is sand filtered and chlorinated by the City of Coalinga before reaching the project. Upon arrival the water is treated with catalyzed sodium sulfite to remove oxygen and then filtered by rotary leaf diatomaceous earth filters (Bates, 1976).

J. Identify and prioritize a priori pollutant concerns--

Accomplishment of this effort requires more detailed and complete outputs from step (I). Such data should be forthcoming within the next year (Silvestro, 1980). As can be seen from the data already available, there is toxicological evidence for concern regarding the use of a number of the potentially used chemical agents. A preliminary discussion of some of the issues is presented here. Chemicals used for enhanced recovery processes include: mobility control agents (MCA's, basically polymers), various preflushing agents, micellar solutions (surfactants and cosurfactants, caustics), bactericides, oxygen scavengers, and drilling muds.[52]

1. Mobility control agents--Several different polymer classes have been used or are planned for use in EOR operations. The conventional mobility control agents, such as polyacrylamides, biopolymers, and others are used to control the displacement and sweep efficiencies. There are also more compounded advanced mobility control agents used such as polyacrylamide-aluminum citrate-polacrylamide (Phillips Petroleum licensed technology) and lignin sulphonate gels (Amoco Chemical Company).

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[52] Drilling muds are also used in conventional recovery. Extensive workover activity and new well construction in old fields will be required in conjunction with enhanced recovery.

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

The polymers most widely used for flooding are high molecular weight polyacrylamide copolymers and biopolymers such as Flocon and Kelzan MF. The molecular weights of the polyacrylamides are an order of magnitude higher than that of the biopolymers. Consequently, much larger concentrations of the latter are needed to achieve a viscosity equivalent to that of a polyacrylamide solution. The mobility of polyacrlamide copolymer solutions is also enhanced because the effective permeability to the aqueous phase is reduced as a result of adsorption and mechanical entrapment of the polyacrylamide molecules. Most polyacrylamides are linear and less susceptible to mechanical degradation than the branched biopolymers. These differences in structure between the two polymer types account for their different hydrodynamic behavior and their selective use in EOR surfactant/polymer projects.

Of concern in evaluating potential pollutants are the degradation products of the various injected polymers. It is not known whether the degradation in products are hazardous. Polyacrylamides are partially hydrolyzed and probably continue to hydrolyze underground over the long residence time of EOR floods, being converted into polyelectrolytes. The electrostatic charges in polyelectrolytes cause the macromolecules to "shrink" in the presence of salt (Morawetz, 1975) and cause the macromolecules to "entangle" in the presence of polyvalent cations (if the polymer is a polyanion) leading to mechanical degradation. As expected, polyacrylamide solutions are very sensitive to salt concentrations and exhibit more severe shear degradation in the presence of calcium ions (Maerker, 1975).

The acrylamide molecule contains two reactive centers and is readily hydrolyzed by basic or acidic catalysts to yield acrylate ion and acrylic acid (ERCO, 1978a).

Polyacrylamide copolymers (molecular weight of 5 to 20 x 10^6) are usually made up of polyacrylamide and its salts. The composition of the polyacrylamide copolymers determines the degree of hydrolysis and the ionic character of the polymer chain. The ionic character can be varied from 100 percent cationic by use of quaternary ammonium sulfate (methylated) salts of acrylamide through 100 percent nonionic by use of polyacrylamide to 100 percent anionic by use of acrylic acid.

Biopolymers are manufactured by fermentation processes. For example, xanthan gum, a high molecular weight heteropolysaccharide, is produced by the Xanthomonas campestris fermentation of carbohydrates. The polymer backbone consists of glucose linkages like those of cellulose with manose and glucuronic acid units in the side chains. The molecular weight is approximately 1 x 10^6.

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Cross-linking agents used as advanced MCAs are multivalent salts such as magnesium chloride, aluminum citrate, aluminum sulfate, and aluminum nitrate. Cross-linking agents work by acting as a catalyst that compounds or complexes the polymer (usually polyacrylamides) by attracting reactive sites of the polymer molecules. Thus, anionic polymers are more reactive than the nonionic polymers and are injected separately from the cross-linking agent since they react so rapidly (Sparkin, 1976). Sodium carboxymethylcellulose can also be cross-linked with several divalent and trivalent ions (Friedman, 1973). Inexpensive materials such as guar gum can be cross-linked with borate ions; the product is, however, very susceptible to bacterial degradation and to interference by trace ions. Lignin sulphonate gels have also been used in near well treatments. Other polymers that already have been tried include hydroxyethyl cellulose (HEC) and polyethylene oxide (Sandiford, 1977). Polyethylene oxide possesses the ability to form peculiar complexes with salts (Bailey, 1976) leading to rapid mechanical degradation in shear analogous to that in polyelectrolytes.

2. Preflushing Agents-- Generally, preflushing agents include pH control agents, cross-linking polymers, and the same polymers described above. Preflushing agents generally are designed to remain in or be consumed in the reservoir and so generally should contribute few pollutants.

3. Surfactants-- Surfactants, used in polymer/micellar flooding, generally are petroleum sulfonates. These substances can be important contaminants of freshwater supplies especially with regard to taste, odor, and the visual problems associated with foaming.

4. Alkalinity, pH Control Additives-- These are products designed to control the degree of acidity or alkalinity of a fluid. These include lime, caustic soda, bicarbonate of soda. As pollutants, these may alter the chemistry of the natural waters.

5. Bactericides-- Bactericides function to reduce bacteria count. Paraformaldehyde, caustic soda, lime, and starch preservatives are commonly used. By their nature, bactericides are mildly toxic and need to be carefully studied.

6. Corrosion Inhibitors-- Hydrated lime and amine salts are often added in systems to check corrosion. Good fluid, containing an adequate percentage of colloids, certain emulsion muds, and oil muds, exhibit in themselves excellent corrosion inhibiting properties. Corrosion inhibitors are often very

BEGIN LAST LINE OF TEXT
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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

reactive and thus their active properties are greatly reduced before the substance has undergone significant transport.

DISPOSAL PROCESSES

Disposal of Waste Waters Associated with Enhanced Gas Recovery

The water quantity required to produce fractures in gas-bearing sands was shown previously to vary considerably depending on the process selected. In addition, there are a variety of technically feasible variations on each approach some of which include injection of potentially hazardous chemicals. Table 59 summarizes the classes of chemicals that are used in enhanced gas recovery and their usual concentrations.

TABLE 59. CLASSES OF MATERIALS USED IN EGR

Material	Concentration Rang	Process
Sand	2-3 lb/gal	Cryogenic, foam
CO_2	25% liquid CO_2	Cryogenic
N	80% Nitrogen	Foam
Bactericide	generally up to 200 ppm	All involving use of polymer
Clay stabilizers	variable	All including clay injection
Polymers	generally up to several thousand ppm	All involving polymer injection
Foaming agent	5 gal/1000 gal	All foaming processes
KCl	2%	Depending on chemistry of mixture

EPA-287 (Cin.)
(4-76)

Most of the fluids employed in generating fractures must be reclaimed from the shale zone before gas production begins. The conventional method of pumping out the water involves the use of mechanical swabbers in conjunction with the natural pressure resulting from the overburden. In processes in which carbon dioxide (cryogenic fracturing) or nitrogen (foam injection) are utilized, the pressure of the additive gas acts to force the water out of the well. This reclaimed water then becomes waste water that, at present, is generally disposed of in a drilling pit. Most of the newer drilling pits have had to conform to environmental regulations involving the use of hazardous waste disposal area liners. These pits act as evaporating pumps for the waste water after which the injected chemicals and any other contaminants that may have been added during the residence time of the water in the rock are present in a concentrated form in the pit. Current practices generally involve the grading over of these pits and replanting them, with the hazardous substances still residing in the surface layer.

Depending on local hydrogeology and the presence or absence of shallow aquifers in the vicinity of enhanced gas recovery operations, enhanced gas processes are clearly potential contributors of hazardous pollutants to groundwater aquifers that may be used for water supplies.

Geological Hazards Associated with Enhanced Gas Recovery

One of the potential hazards associated with fracturing used to induce gas recovery is that communicating fractures may be generated that allow transport of injected fluids (or gas) to coal seams and/or aquifers. It is difficult to provide an assessment of the significance of this risk on a regional or general basis because of the many site specific geological factors. In lieu of such an assessment, the following factors are offered as guidelines for the assessment of risk in particular cases. The best conclusions that can be made at the present time are that:

A) A significant risk may exist in some areas;

B) This risk is due to the lack of complete control over the direction and magnitude of fractures that one wishes to generate; and,

C) Guidelines (regarding spacing of wells and allowable magnitude of individual projects) should be implemented on a county-wide or state-wide basis:

BOTTOM OF IMAGE AREA OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
BEGIN LAST LINE OF TEXT
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

1) Gas-bearing shales often occur at significant depths on the order of 2,000-6,000 feet such that enhanced gas recovery fracturing activities can often be carried out in rock zones that are isolated from mineral zones or aquifers of concern.

2) In many gas shale areas (particularly the Appalachian region), occurrence of coal and of aquifer lenses are associated with the presence of shale. Many of the aquifers occur on a local rather than regional basis such that the geological characteristics of a particular site need to be studied before drawing any conclusions and regional guidelines cannot be imposed on a uniform basis.

3) Although the energy that imposes the shale fracturing can be expected to be considerably extenuated over sedimentary horizons, the magnitude and directions of fracturing cannot be completely controlled. Hence, there must be a considerable margin for error in the design of the fracturing system.

4) Particular problems may develop if individual fracture wells are not spaced at sufficient intervals to avoid interference between the fractured zones generated by the individual wells.

MANUFACTURE OF CHEMICAL FLOODING AGENTS

The polymerization processes most commonly used in EOR are emulsion and suspension polymerizations. There are some technical differences between these two processes, but the potential aqueous pollution problems are not affected by these differences. Basically for both processes, the monomer is dispersed in an aqueous, continuous phase while it is being reacted. Figure 38 is a generalized process flow sheet for a common batch process used to manufacture these polymers.

The waste products from emulsion or suspension polymerization include those that contribute to the wastewater load, and solids from screening or filtering of the batch. The monomers used for the process are often premixed with an inhibitor such as catechol, which must be removed by washing

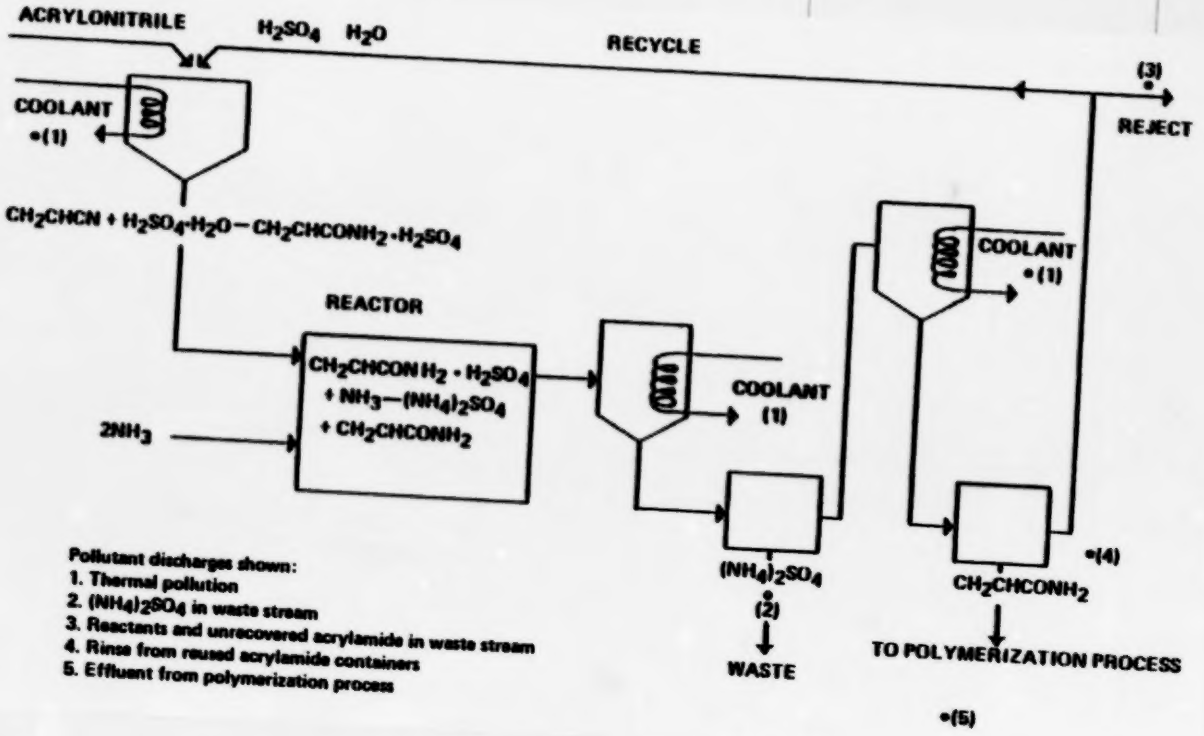
ACRYLONITRILE
H$_2$SO$_4$ H$_2$O
RECYCLE
(3)
REJECT
COOLANT
•(1)
CH$_2$CHCN + H$_2$SO$_4$·H$_2$O – CH$_2$CHCONH$_2$·H$_2$SO$_4$
REACTOR
CH$_2$CHCONH$_2$ · H$_2$SO$_4$
+ NH$_3$—(NH$_4$)$_2$SO$_4$
+ CH$_2$CHCONH$_2$
2NH$_3$
COOLANT
(1)
COOLANT
•(1)
(NH$_4$)$_2$SO$_4$
(2)
WASTE
•(4)
CH$_2$CHCONH$_2$
TO POLYMERIZATION PROCESS
•(5)
Pollutant discharges shown:
1. Thermal pollution
2. (NH$_4$)$_2$SO$_4$ in waste stream
3. Reactants and unrecovered acrylamide in waste stream
4. Rinse from reused acrylamide containers
5. Effluent from polymerization process

Figure 38. Generalized process flow scheme for maufacture of polymer showing pollution potential.

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"
PAGE NUMBER
EPA-287 (Cin.)
(4-76)

prior to polymerization, and this inhibitor-loaded water is part of the aqueous waste. The cooling water and the unreacted monomer are both recycled within the system. Each batch is screened and the oversized screenings are considered solid waste. This resulting small amount of solid waste is disposed of by landfilling.

Some specific details of the manufacture of mobility control agents are presented below:

Polyamides are a category of polymers that includes various nylons and resins. These are usually produced by polymerization of different amino acids. If, as in the case of Nylon 11, the reactions are such "that very little free monomer remains when polymerization is complete (and) wastes developed in the process are negligible" (U.S. EPA, 1975a), then there should be little concern about the secondary, manufacturing impacts.

Ethylene-vinyl acetate (EVA) Copolymers are used in EOR recovery techniques. They are manufactured with the same facilities as polyethylene except for the additional equipment needed for recovery of the unreacted vinyl acetate and ethylene. (U.S. EPA, 1975a). After polymerization the liquid phase is distilled to recover ethylene and vinyl acetate after the EVA has been separated from the liquid phase. When the liquid phase that is separated from the EVA product is distilled, the monomers are recovered for further use and the final waxy residue is incinerated or used as fuel. Any residual ethylene gas is removed and returned to the compressor, so that there is no effluent.

Pollutant generation may occur when the waxy distillation residue is incinerated. However, the EPA report seems to think this is negligible, as it is not mentioned. In terms of waste water, a cooling stream is used in the pelletization of the EVA and this is usually recirculated through the refrigerator cooling system. A purge is maintained on the water to restrict contamination of the recycled water by vinyl acetate and polymer fines. This purging process means that vinyl acetate will be in the waste water. The EPA report (U.S. EPA, 1975a) remarks "vinyl acetate ... from the purge stream is biodegradable both as the intact compound and in the form of its hydrolysis products, acetaldehyde, and acetic acid."

Other possible waste sources include: oil leakage and spills from pumps and compressors and wash down water from processing and loading areas that contain vinyl acetate. These wastes contaminate surface water drainage and are controlled by skimming operations that recover the oil and

EPA-287 (Cin.)
(4-76)

EVA particles. The former is incinerated (with concomitant air pollutants) and the EVA is landfilled or sold to scrap reprocessors (U.S. EPA, 1975a).

The EVA copolymers used in EOR may be distinctly different than the above in that they are produced by an emulsion polymerization process. The emulsion copolymer has a very high vinyl acetate content. According to the report, this type of EVA is only made at one plant and the emulsion polymerization process and associated wastes are similar to polyvinyl acetate homopolymer emulsion.

K. Re-Rank possible pollutants according to amounts, concentrations, and toxicity data--

This effort will result in detailed information on which chemicals should be carefully controlled if they are to be used in enhanced recovery. An index of level of pollutant potential for an individual chemical will be as follows:

$$R_{ct} = W_V V(ct) + W_c C_R(ct) + Ta(cC) + C_1(c)$$

where

R_{ct} = risk of environmental/health damage for technology t by use of chemical c

W_V = weighting function for volume

$V(ct)$ = volume of chemical c used for technology t

W_c = weighting function for concentration

$C_R(ct)$ = concentration in the reservoir for chemical c when used for technology t

$Ta(cC)$ = acute toxicity index for chemical c at concentration C

$C_1(c)$ = low level carcinogenicity or chronic toxicity index for chemical c at concentration $C \times 10^{-2}$

Calculation of these values and interpretation of the results will await additional data that are required to complete [H] and [J].

L,M. Enumerate and assess existing regulatory controls - chemical and physical--

Environmental impediments to the development of enhanced recovery technology must ultimately be evaluated in terms of regulatory constraints. The existing regulations have been

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

reviewed in Section Three of this report. The essential elements of the regulatory structure are as follows:

Existing regulations--

1. Chemical injection. The Toxic Substances Act gives the EPA jurisdiction over the use of chemicals. The EPA has not specifically promulgated standards for control of the use of chemicals in EOR technologies.

2. Reinjection of produced water. The Safe Drinking Water Act provides for control of injection practices near aquifers. No standards for EOR or EGR have been promulgated.

3. Surface disposal of drilling muds and EGR residues. The EPA has classified drilling muds as special wastes under RCRA. This classification is being contested by the oil industry. No specific regulations have yet been developed.

Proposed regulations--

1. Underground injection regulations. The proposed regulations would require well workovers and recementing within a 1 1/4 mile radius of enhanced recovery injection wells.

Major deficits of regulatory structure based on information contained in this report--

1. No list of priority concerns. There has been no list developed by regulatory bodies to identify chemicals of concern and their threshold concentrations. As a result, actions such as general designation of drilling muds as special wastes have little credibility.

2. No monitoring program. There is no monitoring network in place to evaluate the effectiveness of regulations for control of groundwater pollution from enhanced recovery. Hence benefits associated with control investments cannot be evaluated.

3. Further specification of regulatory needs must await development of data required for [H] and [J].

N. Delineate expected persistent groundwater pollution problems--

The most serious groundwater risk attributable to enhanced recovery is the temporary nature of the existing waste disposal practices. Enhanced recovery injection together with reinjection of brines leaves us with hazardous liquid bodies residing in subsurface formations. These hazardous wastes then have the potential to become mobilized upon structural or chemical alterations of the geology of the reservoir locale. Hence, generation of such hazardous fluids should be minimized and where subsurface disposal occurs, mapping of contaminated zones should be required. Careful monitoring of these sites is required. Further development of this analytical step will await development of data needed for [H] and [J].

O. Suggest control strategies--

This final stage in the analysis of groundwater concerns and their control is covered in Section Five.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

SECTION FIVE

POLLUTION CONTROL FOR EOR/EGR SYSTEMS

INTRODUCTION

This chapter presents a characterization of the technologies available for control of the pollutants discussed in Section Four. The section first describes major control technology issues, summarizes the options, then discusses pollutants on a medium-by-medium basis, and then discusses tradeoffs.

For each environmental medium, control technologies presently in use or under development are identified and presented. When data are available, the control technologies are also compared in terms of their efficiency and cost. No attempt is made to analyze the technological options in search of an optimum; available data are merely displayed in comparable form where such data are available.

A summary is made of several of the control and process options and the intermedia tradeoffs consequently involved in the ultimate selection of a recovery strategy for a specific site.

The availability of proven control technologies can generally be correlated to the historical regulation for each medium. Of the four pollutant media - noise, air, surface water, and groundwater - control technology options have been most developed for control of noise and air emissions. For these media, a variety of specific control devices exist. For surface water pollution control, there is also a host of technologies available, but determinations have yet to be made of the specific surface water pollutants appearing around EOR sites, and the potential magnitude of their impacts, before controls can be recommended. The non-point source nature of groundwater polluting events makes specification of appropriate technologies difficult.

OPTIONS FOR CONTROL

The previous sections of this report have assembled the available information regarding the nature and impact of the

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

pollutants released by enhanced oil and gas recovery processes. This section provides a preliminary discussion of control approaches that can be followed to reduce the environmental and health risks associated with the enhanced recovery technologies. Decisions regarding (1) investment in the development of new control technologies, (2) retrofitting, and (3) installation of control measures in new projects rest upon tradeoffs between the risk reduction obtained (the environmental and health benefits) and the economic/energy penalties incurred.

An analysis of such tradeoffs must be made and a set of reasonable control strategies that minimize the environmental risks associated with each EOR process must be formulated. Some means of determining whether the levels of risks remaining are acceptable must be devised. If the risks remaining after implementation of the primary control strategies are unacceptable, alterations in individual EOR process designs will be necessary in order to mitigate the pollutant problems remaining after implementable control technologies have been applied.

Detailed development of threshold levels of acceptable risk for pollutants from an enhanced recovery technology is well beyond the scope of this effort; however, some idea of the dimensions of the problem sufficient for preliminary investigation of control technologies can be obtained from existing standards. The problem with the use of these existing standards is that in many cases standards have not been developed specifically with oil recovery technologies in mind. Therefore, some of the pollutants that are generated by these technologies are not covered under existing regulations. It may be possible to meet all the terms of existing regulations while still allowing discharges that result in health and environmental risks. As these currently unregulated pollutants are studied and controlled by new regulations and criteria, additional pollution control costs will be incurred to satisfy the intent of current pollution control legislation. These pollutants can be anticipated to include primarily organics discharged to air and water.

A factor that further complicates the implementation of environmental controls is the problem of intermedia tradeoffs. A simple example of this problem as it occurs in steam soak projects is the problem of air pollution controls of sulfur emissions. The most effective means for reducing sulfur oxide emissions is by the so-called "scrubbing" of oxides out of the air stream by use of reactant substances that then generate a hazardous solid waste requiring disposal. Thus, air quality is improved at the expense of solid waste disposal problems with the associated hazards of groundwater contamination by leachate. These intermedia tradeoffs tend to be maximized in

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EPA-287 (Cin.)
(4-76)
PAGE NUMBER

high technology engineering solutions to exotic pollutant problems. Minimizing the need for highly sophisticated and engineered control equipment is desirable to minimize generation of cross-media wastes.

In general, three main approaches have been considered by this study for the control of enhanced recovery waste products. Each of these three classes of controls is briefly described below.

Careful Management of Recovery Technology Selection, Reservoir Engineering, and Production Practices

Specific pollutant problems can often be ameliorated by the selection of alternative methods for accomplishing a particular engineering or production function. Some examples of this form of environmental control include changing the locations of steam generators to maximize atmospheric dispersion and thus minimize SO_x and NO_x concentrations in the atmosphere, scheduling drilling and excavation activities so as to minimize exceeding EPA noise standards during nighttime hours, and substitution of chemicals in the flooding sequence to minimize use of substances with dangerously high toxicity ratings.

Ambient Controls

In some instances, pollutant impacts can be minimized by augmenting the receiving medium's ability to disperse or cycle an introduced pollutant. Examples of these measures include erection of noise barriers to control the intensity and extent of noise, utilization of high stacks to aid air pollutant dispersion, and control of subsurface flows.

Effluent/Discharges Controls

Use of control devices at the point of pollutant discharge constitutes the classic pollution control strategy. A variety of air and water control processes are available in pilot and commercialized forms.

SUMMARY OF AVAILABLE SOLUTIONS

Table 60 summarizes the available means for control of enhanced recovery pollutants and consumptive water use. General levels of cost and effectiveness are presented. The table is arranged according to pollutant types organized in terms of different media affected and analyzed in terms of control options, category of control, technological constraints, control effectiveness, estimated cost, and hypothesized oil production penalty. The pages that make up

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TABLE 60. SUMMARY OF CONTROL OPTIONS

A. CONTROL OF DISCHARGES OR EMISSIONS

		Category of Control			Technological Constraints				Effectiveness		
			Structural								
Pollutant Type	Control Option	Non-Structural	Effluent	Ambient	Currently Infeasible	Currently at Developmental Stage	Commercially Available	No Technological Constraints	Accomplishes Some Amelioration	Meets Existing Standards	Meets Existing Standards and Reduces Additional Unregulated Risks
1. **NOISE** A. Drilling, reworking, construction noise	(i) Schedule activities to minimize nighttime work	X						X	X^2		
	(ii) Require mufflers		X				X			X^2	
	(iii) Portable noise barriers			X			X			X^2	
B. Steam recovery generator noise	(i) Permanent noise barriers			X			X			X	
	(ii) Locate generators away from other land uses	X						X	X		
C. CO_2, N_2, other compressors	(i) Permanent noise barriers			X			X			X	
	(ii) Locate compressors away from other land uses	X						X	X		
	(iii) Utilize mufflers		X				X			X	
2. **AIR**											
A. Motors for construction equipment, pumps, and other miscellaneous needs	(i) Limit total allowable emissions from such sources	X						X		X	

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EPA-287 (Cin.)
(4-76)

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A. CONTROL OF DISCHARGES OR EMISSIONS (cont.)

TABLE 60. (continued)

Pollutant Type	Control Option	Cost: Low < 0.50 Barrel	Cost: Medium 0.50-1.50/ Barrel	Cost: High > 1.50 Barrel	No Effect	Production Penalty: Reduces Production Yield	Production Penalty: May Render Technology Ineffective	Comments
1. **NOISE**								
A. Drilling, reworking, construction noise	(i) Schedule activities to minimize nighttime work					x		24 hour-per-day activities cannot be avoided if projects are to be economical
	(ii) Require mufflers		x[1]		x			Mufflers not available for all equipment, economic impact analysis not available for all equipment
	(iii) Portable noise barriers		x[3]		x			
B. Steam recovery generator noise	(i) Permanent noise barriers		x[3]		x			Barriers constitute an aesthetic environmental concern
	(ii) Locate generators away from other land uses	x[3]				x		In many cases steam operations are already remote from other activities
C. CO_2, N_2, other compressors	(i) Permanent noise barriers		x[3]		x			Barriers constitute an aesthetic environmental concern
	(ii) Locate compressors away from other land uses	x[3]				x		In many cases applications are already remote from other activities
	(iii) Utilize mufflers		x[1]			x		
2. **AIR**								
A. Motors for construction equipment, pumps, and other miscellaneous needs	(i) Limit total allowable emissions from such sources	x[3]				x		May limit total production capacities dependent on emission offset used in each airshed

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PAGE NUMBER
EPA-277 (Cin.)
(4-76)

TABLE 60 (continued)

A. CONTROL OF DISCHARGES OR EMISSIONS (cont.)

Pollutant Type	Control Option	Category of Control: Non-Structural	Category of Control: Structural: Effluent	Category of Control: Structural: Ambient	Technological Constraints: Currently Infeasible	Technological Constraints: Currently at Developmental Stage	Technological Constraints: Commercially Available	No Technological Constraints	Effectiveness: Accomplishes Some Amelioration	Effectiveness: Meets Existing Standards	Effectiveness: Meets Existing Standards and Reduces Additional Unregulated Risks
2. **AIR** (cont.) B. Steam generators	(i) Limit total allowable steam generators	x						x		x^4	
	(ii) Require grouping of sources in locales to maximize dispersion	x					x		x^4		
	(iii) Utilize scrubbers, NO_x, particulate control devices		x			x^a	x^a				$x^{5,a}$
	(iv) Utilize low sulfur coal	x					x^b				
	(v) Utilize fluidized-bed gasification and/or low sulfur coal in steam generation		x			x				x	
C. Fugitive emissions of gases produced during enhanced recovery	(i) eliminate hazardous fugitive sources		x		x^c		x^c		x		
3. **SURFACE WATER** A. Scrubber water	(i) Dilute and reinject with produced water			x			x			x	
	(ii) Chemical/ physical treatment		x				x				x
B. Hydrocarbon spills	(i) Implement spill control precautions	x^d	x^d				x		x		
	(ii) Utilize soil cleanup procedure			x			x			x	
C. Produced water	(i) Reinjection			x			x			x	
	(ii) Inject to isolated subsurface layer			x			x				x
	(iii) Chemical/physical treatment and reuse		x			x					x

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EPA-287 (Cin.)
(4-76)

TABLE 60 (continued)

A. CONTROL OF DISCHARGES OR EMISSIONS (cont.)

Pollutant Type	Control Option	Cost: Low < 0.50 Barrel	Cost: Medium 0.50-1.50/ Barrel	Cost: High > 1.50 Barrel	No Effect	Production Penalty: Reduces Production Yield	Production Penalty: May Render Technology Ineffective	Comments
2. **AIR** (cont.) B. Steam generators	(i) Limit total allowable steam generators	x[4]					x	Will limit total production capacities
	(ii) Require grouping of sources in locales to maximize dispersion		x[4]			x		
	(iii) Utilize scrubbers, NO_x, particulate control devices			x[5]	x			It has not yet been demonstrated that the control technologies will operate effectively on a continuing basis
	(iv) Utilize low sulfur coal		x[5]		x			Not available without high transportation costs
	(v) Utilize fluidized-bed gasification and/or low sulfur coal in steam generation			x[5]	x			Several new technologies are becoming available for steam generation but have not yet been applied to EOR operations
C. Fugitive emissions of gases produced during enhanced recovery	(i) eliminate hazardous fugitive sources	U N K N O W N			x			Fugitive sources have not been well categorized to date
3. **SURFACE WATER**	(i) Dilute and reinject with produced water	x[9]			x			Only feasible for small flows of wastewater
A. Scrubber water	(ii) Chemical/ physical treatment		x[3]		x			Only feasible for large flows in a locale
B. Hydrocarbon spills	(i) Implement spill control precautions	x[10]				x		
	(ii) Utilize soil cleanup procedure		x[10]		x			
C. Produced water	(i) Reinjection		x[11]		x			Future regulations may make costs of this option prohibitive
	(ii) Inject to isolated subsurface layer			x[11]	x			Future regulations may make costs of this option prohibitive
	(iii) Chemical/physical treatment and reuse			x[3]		x		This option also helps to solve the consumptive water use problem

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TABLE 60 (continued)

A. CONTROL OF DISCHARGES OR EMISSIONS (cont.)

Pollutant Type	Control Option	Category of Control			Technological Constraints				Effectiveness		
		Non-Structural	Structural								
			Effluent	Ambient	Currently Infeasible	Currently at Developmental Stage	Commercially Available	No Technological Constraints	Accomplishes Some Amelioration	Meets Existing Standards	Meets Existing Standards and Reduces Additional Unregulated Risks
4. **GROUNDWATER** A. Leaks from well casings	(i) Reworking of old wells		x				x				x
	(ii) Continual monitoring of injection pressure with quick-response plan ready		x				x				x
	(iii) Periodic casing, crack, & tube replacement		x				x				x
	(iv) Injection at reduced pressure	x					x		x		x
	(v) Control measures for sulfate reducing bacteria which generate corrosives	x					x[e]				x
B. Migration of reservoir fluids to neighboring strata	(i) Cross linking polymers	x					x				x
C. Solid waste leachate	(i) Use of pit liners		x				x		x		
	(ii) Composting, pyrolysis, or incineration		x				x		x		

FOOTNOTES:

[a] Control equipment is commercially available. However, existing scrubber units are not performing at or near design specifications (e.g., Chevron-Kern County and Shell-Cat Canyon units). The best working systems are individually modified commercial systems.

[b] Feasibility tied to proximity of resource.

[c] Some fugitive sources, such as H_2S venting, can easily be controlled. Other sources, such as miscellaneous gas leaks, have not yet been identified or fully assessed and therefore cannot currently be controlled.

[d] A range of measures exists.

[e] Process is available but its effectiveness may be limited to certain reservoir settings.

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TABLE 60 (continued)

A. CONTROL OF DISCHARGES OR EMISSIONS (cont.)

Pollutant Type	Control Option	Cost: Low < 0.50 Barrel	Cost: Medium 0.50-1.50/ Barrel	Cost: High > 1.50 Barrel	No Effect	Production Penalty: Reduces Production Yield	Production Penalty: May Render Technology Ineffective	Comments
4. GROUNDWATER A. Leaks from well casings	(i) Reworking of old wells	X^3			X			
	(ii) Continual monitoring of injection pressure with quick-response plan ready	X^3			X			
	(iii) Periodic casing, crack, & tube replacement	X^3			X			
	(iv) Injection at reduced pressure	X^3				X		This option could significantly reduce technological feasibility
	(v) Control measures for sulfate reducing bacteria which generate corrosives	X^3	X^3		X			Bacterial control methods are still largely at a developmental stage
B. Migration of reservoir fluids to neighboring strata	(i) Cross linking polymers		X	X		X		
C. Solid waste leachate	(i) Use of pit liners		X		X			Ultimate disposal problem still remains
	(ii) Composting, pyrolysis, or incineration	X	X		X			Allows reclamation of energy value, may impose air pollution

NOTES ON DATA SOURCES:

	[1] EPA Noise Office	[5] ERCO, 1978	[9] Based on Getty Cat Canyon Pilot Venture
	[2] OSHA	[6] ERCO, 1979	[10] EPA Oil Spill Staff, Edison, New Jersey
	[3] ERCO Estimate	[7] API	[11] API, 1979
	[4] SAI, 1978	[8] EPA Underground Injection Control Regulations	

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 60 (continued)

B. REDUCTION OF CONSUMPTIVE WATER USE

Pollutant Type	Control Option	Technological Constraints		Potential Reduction In Consumptive Use (in % of total water use by EOR)		Cost			Production Penalty		
		Currently Infeasible	Currently at Pilot Stage	Now	When Technology Becomes Commercial	Low <0.50/ Barrel	Medium 0.50-1.50/ Barrel	High >1.50/ Barrel	No Effect	Reduces Production Yield	May Render Technology Ineffective
PROCESS WATER SUPPLY	(i) Treatment and reuse of produced water (= 3.C.iii above)		X	0-5%	20-30%			X		X	
	(ii) Treatment and use of other brines		X	5-10%	50-100%		X			X	

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Table 60 should be viewed in pairs, the second pages being horizontal extensions of the first.

The following is a presentation of available data on control technology efficiency and the costs incurred for implementation of existing control technology. The discussion is developed separately for each of the following media:

Noise
Air
Surface water
Groundwater

Solid wastes are not treated directly, but are considered with respect to their ultimate impact on groundwater through the leaching of hazardous substances.

Noise Controls

Reduction of noise levels during the production phase of oil recovery operations can be effected by several control strategies. The noise can be reduced at its source; noise radiation can be limited by use of baffles, barriers and the like; or ear-protective equipment can be employed. In terms of reduction of noise at its source, several control strategies are available for specific sources.

To decrease the high noise impacts of diesel engines, which often power pumps, compressors, and generators, options include mufflers, enclosure in sound-proofed buildings, use of portable sound barriers, ear protectors for those on-site, and substituting quieter electric motors for the diesels. Mufflers or silencers can also reduce the noise of venting gases and reciprocating valves, while portable barriers or ear protectors are the currently feasible choices for short-term drilling and well-repair operations.

The impact of noise produced by the traffic associated with EOR operations can be reduced by routing and scheduling these activities to conform with background noise levels. The available options can include: regulating the amount of heavy vehicle traffic on given routes, routing to minimize passage near residential areas, scheduling traffic passage during the day rather than in the (relatively quieter) evening, and enforcing strict speed control on vehicle operators.

The available controls vary in effectiveness and in cost to operators. Generally, enclosing machinery within soundproofed buildings is most effective because the problem is essentially contained. However, this option is also usually considered to be most expensive because of the costs of the

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

building, lighting and ventilation that are necessary. Mufflers can also be expensive, adding as much as 25 percent to the cost of equipment being silenced yet varying in their effective noise-reduction. Ear-protectors can be effective on-site in reducing noise impact on the individual wearing them but they may have hidden costs in terms of educational and promotional programs to encourage workers to wear them, safety problems when workers cannot communicate verbally, and supervision to see that the ear-protectors are worn.

Air Pollution Control Options

The major steam flooding activity currently occurs in California in and about Kern County (Noran, 1978).[53] The California Air Resources Board (CARB) has established or approved the following emissions regulations for the Kern County area that directly affect steam flooding activity:

1. All stationary combustion sources emitting more than 100 tons/year of SO_x, NO_x, particulates, non-methane hydrocarbons, or 1000 tons/year of CO, should have monitors on the source to measure the emissions (not required but suggested).

2. Ambient Statewide Air Quality Standards: In no case can the current district air quality be degraded by the addition of new sources if the statewide air quality standards are being exceeded (See Table 61).

3. Stationary combustion sources-- Regulations on new and existing boilers for steam drive EOR applications have been proposed (by CARB) with an effective compliance date of September 1980 for all boilers greater than 5 MMBtu/hr capacity (see Table 62).

   The CARB is already preventing operation of boilers not meeting those standards. Chevron and Getty have announced their intention to halt EOR development in California as long as these air quality constraints exist (Noran, 1979).

Sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulates are all generated by EOR steam generators. Attention centers on these emissions because current emission levels in Kern County, California, produce ambient sulfur dioxide and smog

---

[53] Other steam flooding activity is planned for coastal regions and these are also likely to have severe environmental constraints.

EPA-287 (Cin.)
(4-76)

TABLE 61. AMBIENT STATEWIDE AIR QUALITY STANDARDS[a]

Species	Maximum Allowable Concentration, ppm	Allowable Duration in Hours During Which Standard Can Be Exceeded
CO	10	12
	40	1
SO_2	0.5	-
	0.05	if oxidant standard is being exceeded or state 24-hour particulate standard is being exceeded concurrently
Particulates	60 mg/m^3	24
NO_2	0.25	1

[a] California Air Resources Board, 1978

TABLE 62. PROPOSED LEVELS OF CONTROL FOR EOR STEAM GENERATORS[a]

	Existing Boilers	New Boilers
All sulfur compounds (as SO_2)	200 ppm[b]	60 ppm[b]
Nitrogen compounds (as NO_2)	150 ppm[b]	100 ppm[b]

[a] CARB, proposed 1978.

[b] Reduced to a 3 percent oxygen level in the flue gas on a moisture free basis.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

levels above regional California standards. California Air Resources Board (CARB) action to shut down expansion of steam recovery in Kern County because of noncompliance has generated widespread interest in effective controls for these emissions. However, most controls are still in a developmental stage and constant technological changes make EOR air emission control cost data difficult to estimate (Radian, 1979). The control options for these pollutants are discussed below in terms of technology and economics. Data addressing the emissions levels and removal of hydrocarbons, H_2S, CO, and O_3 are not available.

SO_x Removal--

The control technologies applicable to the control of SO_x, NO_x, and particulates are dependent on the existing enhanced recovery technique. As noted in a previous section, monitoring and control efforts have focused only on the emissions from steam boilers; however, emissions from other above-ground processes are probably not significant. Possible emissions problems associated with in situ combustion have not been evaluated by collection of field data.

The control options for steam generators include both add-on clean up packages and process changes. The most commonly accepted add-on control for SO_x is flue gas desulfurization (FGD) or stack gas scrubbers.

In the sulfur dioxide scrubbing process the flue gas containing sulfur oxides is brought into contact with a liquid phase containing a chemically active material that reacts with the sulfur oxides, leaving a sulfur-containing compound dissolved in the liquid phase. Thus the process involves mass transport of SO_x from a gas to a liquid phase followed by chemical reaction.

A large number of absorption solutions and processes have been proposed, and some evaluated, to scrub SO_2 from stack gases. Most of the scrubbers that are currently operational are installed in electric power plant utility systems. Here the scrubbers are manned and controlled since reliability and availability are the primary parameters considered by the utility industry. As of June 1977, a total of 119 FGD units were operational, under construction, or planned. Over 90 percent of operational units and 85 percent of those under construction used some variation of lime/limestone as the chemical absorbent in which a wet $CaSO_4/CaSO_3$ sludge had to be disposed of. Scrubber reliability has been the major complaint for these systems. Most of the problems have occurred with systems installed early on in scrubber development and reliability has improved as the technology has advanced.

EPA-287 (Cin.)
(4-76)

Emissions from individual steam generators must be ducted together in order to maximize economies of scale in gas scrubbing. Current practice has been to attempt to scaledown the SO_x scrubbing systems developed for utility and industrial boilers, while ducting together emissions from six to ten ($5-50 \times 10^6$ Btu/hr) steam generators.

Tables 63 and 64 outline operating parameters and developmental status of FGD systems utilizing various chemical processes. The lime/limestone-based processes generate substantial volumes of sludges, which are being evaluated by EPA as a possible hazardous waste. This is a result of the large amount of trace elements that are also filtered out of the stack gases and end up in the sludge.

Most steam drive generators for EOR application are currently not fitted with scrubbers for SO_2 control. The few scrubbers that are in operation, after usual startup difficulties, appear to be working well as far as SO_2 control. However, these scrubbers in general produce a fine particulate load that is carried with the combustion gas into ambient air. These systems may exceed the particulate emissions or sulfur standards if the particulate emissions contain sulfur-bearing compounds. Table 65 provides a brief synopsis of several of the scrubbers in operation or planned for operation in the near term.

Of primary concern to the California oil field operators are that:

a. scrubbers meet SO_2 standards without generating particulate mist problems;

b. scrubbers operate reliably without scaling or plugging problems;

c. scrubbers operate largely unattended to reduce labor cost for oil production; and

d. scrubber capital and operating costs are not exorbitant so as to significantly increase the cost of produced oil.

These considerations and the operating experience with existing systems must come into play in developing and evaluating scrubbers for steam drive EOR applications.

The status of the remaining FGD systems as well as several others that are not presently being considered for application is displayed in Table 66. Additionally, a pilot ammonia scrubbing process is undergoing investigation in Canada. This

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EPA-287 (Cin.)
(4-76)

TABLE 63. OVERVIEW AND SUMMARY OF EXISTING SCRUBBER SYSTEMS[a,b]

	Evaluation Factor							
			Secondary Impacts					
Control Process	SO_2 Removal Ability	Multi-pollutant Control	Air	Water	Solids	Relative Material and Energy Intensiveness	Development Status	Process Controllability Problems
Lime/limestone wet scrubbing process	>90% demonstrated	Some particulates	None	Solids leachate (metal)	Significant sludge quantities for disposal	Sorbent, water, electricity -- all moderate	Commercial or utility scale	Scaling, plugging, variable efficiency
Sodium/lime double alkali process	>95% demonstrated	Some particulates	None	Salt leachate	Sludge volume large	Sorbent, water, power - all moderate	Small demos to date; commercial, Japan	Scaling, sulfate buildup, poor sludge quality
Wellman-Lord process	≥99% demonstrated	Some fly ash and HCl	Carryover of entrained mist and fugitive dust	Minimal	Sodium sulfate solids	Large steam/water requirement; sorbent, power-moderate	Commercial, especially in Japan	Rate of sulfate formation
Magnesia slurry absorption process	>90% demonstrated	SO_3 removal suspected	Possible Mg compounds, particulates, fugitive dust	Minimal	None*	Energy intensive; low materials requirements	Commercial	Solids handling only
Atonics International aqueous carbonate process	90-95%	Some particulates	Possible H_2S	TDS in effluent cooling water	Minimal	Material and energy requirements moderate	Pilot scale; demo planned 1978	Spray dryer & reducer control difficult
Citrate/phosphate buffered absorption process	>99% capability	Some particulates	Possible H_2S	Phosphate solution & citrate absorbing liquor	Minimal	Material and energy requirements relatively low	Pilot scale; demo planned 1978	Regulation of H_2S to prevent odor

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[a] U.S. EPA, 1977b.

[b] This table reflects utility-scale applications

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 63. (continued)

	Evaluation Factor				
	Applicability Considerations				
Control Process	Utilities	Industry	Useful Byproducts	Process Alternatives	Comments
Lime/limestone wet scrubbing process	Sludge disposal; land required	Should be applicable	Gypsum	Mass transfer additives concurrent scrubbing forced sludge fixation	Best developed, most advanced system
Sodium/lime double alkali process	Easy retrofit; land required	Applied successfully to small boilers	Gypsum	Sulfate removal, forced oxidation, regeneration with limestone, alternative absorbents	Reliable & efficient operation; good SO_2 removal
Wellman-Lord process	Well-suited	Should be well-suited	Sulfur or H_2SO_4	Double effect evaporates S vs H_2SO_4 production	High SO_2, removal efficiency
Magnesia slurry absorption process	Land required; complex	Limited, due to high cost	H_2SO_4	Sulfur production	Minor disposal; low raw materials, minor plugging
Atomics International aqueous carbonate process	Space required for retrofit	Limited, due to complexity of regeneration	Sulfur	Carbonization process; reducing agent	Produces sulfur readily
Citrate/phosphate buffered absorption process	Easy retrofit; load following difficult	May be limited due to complexity	Sulfur	Double-loop regeneration; buffer alternatives; McKee modification	High SO_2 removal efficiency

EPA-287 (Cin.)
(4-76)

TABLE 64. DISTRIBUTION OF FGD SYSTEMS BY CHEMICAL PROCESSES[a]

	FGD Capacity, MW			
Process	Operational	Under Construction	Planned	Total
Limestone[b]	8,734	8,687	10,848	28,269
Lime[c,d]	6,070	6,029	3,482	15,581
Lime/Limestone	20	330	330	680
Sodium carbonate	375	509	0	884
Magnesium oxide	120	0	1,326	1,446
Wellman Lord	735	180	940	1,855
Dual alkali	0	1,102	0	1,102
Aqueous carbonate[e]	0	400	100	500
Citrate[f]	0	60	0	60
TOTAL[g]	6,054	17,297	17,026	50,377

[a] Pedco Environmental, Inc., 1979.

[b] Includes alkaline fly ash/limestone and limestone slurry process design configurations.

[c] Includes alkaline fly ash/lime and lime slurry process design configurations.

[d] Includes nonregenerable dry collection process design and nonregenerable wet scrubbing process design configurations.

[e] Includes nonregenerable dry collection process design and regenerable process design configurations.

[f] This system is being installed at St. Joseph Minerals' G.F. Wheaton Plant and is listed as a utility FGD system because the plant is connected by a 25-MW interchange to the Duquesne Light Company.

[g] Because the processes for all planned systems are not known, the totals in this table are less than the actual projection of FGD system demand.

EPA-287 (Cin.)
(4-76)

TABLE 65. SUMMARY OF SCRUBBERS OPERATING ON STEAM DRIVES FOR EOR APPLICATIONS[a]

Facility	Number of Scrubbers	Steam Drive Generation Capacity Scrubbed	Scrubber Type Manufacturer	Comments
Chevron	3 existing 2 planned	850 MMBtu/hr 500 MMBtu/hr	Soda ash, Koch Engineering	The systems were designed for 90 percent sulfur removal and 96 percent has been attained. Particulate mists have been observed. Plans are to put a spray in the demisting section to control particulate emissions.
Husky Oil	1 existing	22 MMBtu/hr	Produced alkaline water scrubber with ammonia pH control, Heater Tech, Ponca City, Oklahoma	No problems after changing initial recirculating pump from cast iron to stainless steel. Particulate mists are being generated.
Getty Oil	1 existing	50 MMBtu/hr	Sodium carbonate, FMC Corporation	A problem in generating particulates mainly because of high gas velocity in scrubber. Currently down while Koch Flexi-trays are being installed to correct particulate mist emissions. Will be tested by California Air Resources board when trays are installed.
Chanclor Western Oil Company	1 planned	50 MMBtu/hr	Dual alkali, FMC Corporation	Planned to be completed in 2 years.
Texaco	1 existing	50 MMBtu/hr	Produced alkaline water, no ammonia control, Mustang Engineering	None
Mobil Oil	1 existing	22 MMBtu/hr	Produced alkaline water with ammonia pH control	None. Also experimenting with sodium hydroxide scrubbing.

[a] ERCO, 1978b.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 66. MAJOR EMERGING FGD PROCESSES INVESTIGATED IN THE UNITED STATES[a,b]

Process	Developer	Current Level of Development	Previous Operating Experience	Remarks
Aqueous carbonate	Rockwell International	100-MW system (planned)	Mohave pilot plant test program	Full-scale application not yet demonstrated. 100-MW demonstration system scheduled for service in 1980.
Catalytic oxidation	Monsanto	100-MW system (terminated)	Wood River test program	No further process development.
Chiyoda Thoroughbred 101	Chiyoda International	20-MW system (terminated)	Scholz prototype test program	Development of the process has ceased in favor of a new design concept (Thoroughbred 121, which employs limestone reagent in a jet bubbler reactor).
Copper oxide adsorption	Shell/Universal Oil Products	Pilot plant	Big Bend test program	Process available for prototype or demonstration application. No systems planned at present.
Dual alkali	A.D. Little/ Combustion Equipment	227-MW system (construction)	Scholz prototype test program	Full-scale application not yet demonstrated. A 227-MW demonstration system scheduled for initial operation in early 1979.
	FMC	250-MW system (construction)	Industrial systems and utility pilot plants	Full-scale application not yet demonstrated. A 250-MW system is scheduled for service in 1979.
	Buell/Envirotech	575-MW system (construction)	Gadsby pilot plant test program	Full-scale application not yet demonstrated. A 575-MW system is scheduled for service in 1979.
Dry adsorption	Foster Wheeler Bergbau Forschung	20-MW system (terminated)	Scholz prototype test program	No further development of system reported. Further evaluation of the sulfur reduction component (RESOX) in progress in Germany.
Dry collection	Wheelabrator-Frye Rockwell International	410-MW system (planned)	Leland Olds and Bowen Engineering pilot plant test programs	Successful testing has resulted in the planning of a full-scale spray dryer and fabric filter FGD system at the Coyote Station.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 66 (continued)

Process	Developer	Current Level of Development	Previous Operating Experience	Remarks
Dry collection (cont.)	Joy/Niro	455-MW system (planned)	Leland Olds pilot plant test program	Successful pilot plant testing has resulted in the planning of a full-scale system at Antelope Valley. This system will use lime slurry as the reagent in a 2-stage atomizer/fabric filter design configuration.
	Babcock & Wilcox	550-MW system (planned)	Basin electric pilot plant test program	Successful pilot plant testing has resulted in the planning of a full-scale system at Laramie River. This system will use lime slurry as the reagent in a configuration that employs an ESP as the second stage collector.
	Carborundum/ Delaval	Pilot plant	Leland Olds pilot plant test program	Process similar in design to the Wheelabrator-Frye/R.I. and Joy/Niro processes. No full-scale applications have yet been announced.
Magnesium oxide	Chemico	150-MW system (terminated) 95-MW system (terminated)	Mystic test program; Dickerson test program	Process demonstrated on full-scale oil- and coal-fired boilers. System now offered for commercial application.
	United Engineers	600-MW system (planned)	Eddystone test program	Eddystone 120-MW prototype test program still in progress. A full-scale 600-MW system is now planned for TVA's Johnsonville station.
Sodium carbonate	A.D. Little/ Combustion Equipment Associates	three 115-MW systems (operational)	Reid Gardner Station	Three full-scale sodium carbonate (trona) FGD systems have been in service on coal-fired boilers at the Reid Gardner Station (Nevada Power). System perforance has been good.
	Universal Oil Products	509 MW system (planned)	Jim Bridger pilot test program	A full-scale sodium carbonate (30% sodium carbonate purge solution from soda ash plant) FGD system is now being planned for the Jim Bridger Station.
Wellman Lord	Davy Powerglas	115-MW system (operational) 375-MW system (operational) 340-MW system (operational)	Crane test program	115-MW NIPSCO/EPA test program still in progress at Mitchell. Two full-scale systems have recently started operations at Public Service of New Mexico's San Juan Station.

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[a] Pedco Environmental Inc., 1979.

[b] These processes have been developed mainly for large-scale utility applications. Some of them may be of limited applicability for oil field use.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

process, which is expected to simultaneously remove 90 percent of both SO_2 and NO_x, will be tested on a 20-MW unit by Commico, Air Products, and Chiso Engineering. It reduces the sulfur content of the crude prior to burning and may have potential for future application in lowering the sulfur content of all crude produced in order to raise its market value.

The process changes applicable to reduction of SO_x emissions in EOR technologies are the substitution of low sulfur fuel for the high sulfur crude oil produced at the site or possibly flexicoking of heavy crude to remove sulfur from the high sulfur crude.

Steam boilers can be powered by lower sulfur oil, natural gas, or low sulfur coal purchased elsewhere. However, these fuel changes will incur transportation costs, may incur higher fuel costs (for low sulfur or refined oil), and (for coal) will generate particulate (fly ash) and solid waste (bottom ash) disposal costs. Fluid bed pyrolysis/combustion technologies are currently being developed and tested for the reduction of SO_x emissions, even from high sulfur coal. Increasing discrepancies in fuel costs (oil becoming more expensive relative to coal and low sulfur coal becoming more expensive relative to high sulfur coal) may make fluid bed combustion a more acceptable technology, even within the constraints imposed by transportation and adaptation.

Variables which must be considered in estimating costs of SO_x removal from the flue gas of the small steam generators used in EOR include:

1. fuel type (crude oil, refined oil, coal),
2. fuel sulfur content,
3. desulfurization technology (FGD of various types),
4. generator type (most significantly, size),
5. total gas to be scrubbed (number of generators ducted together), and
6. degree of control required (percent removal).

Data for assembly of cost scenarios involving all of these factors are not generally available and is therefore beyond the scope of this project. However, estimation of flue gas desulfurization costs for conventional EOR systems (high sulfur crude-oil fired 50 MBtu generators ducted together in groups of six to ten) can be estimated from information supplied by oil companies and the DOE. As shown in Table 67, the average cost estimate for flue gas desulfurization for steam flood operators is currently between \$0.30 and \$0.60 per barrel of produced oil.

TABLE 67. SO_x CONTROL COSTS[a,b]
(subject to various uncertainties noted in the text)

Source	Capacity Btu/hr	# of Boilers	# of Scrub-bers	%S	Removal Effi-ciency	Cost ($1978) Capital	Cost ($1978) O&M	Cost ($1978) Total/bbl Produced
Chevron	900×10^6	18	3	1.1	90	2.8×10^6 $(0.14 \times 10^6/yr)$	$0.9 \times 10^6/yr$	0.34-0.26
Mobil	840×10^6	40	30	2-2.5	90	2.9×10^6 $(0.15 \times 10^6/yr)$	$1.3 \times 10^6/yr$	0.38-0.52
Dept. of Energy	$300\text{-}500 \times 10^6$	6-10	1	-	90+	2.6×10^6 $(0.13 \times 10^6/yr)$	$2.6 \times 10^6/hr$	0.4 - 0.6

[a] Assumed operation of 7,200 hours (300 days) per year
Amortization life of the scrubber = 20 years
6.5×10^6 Btu/bbl crude oil
3-4 bbl of oil are produced/bbl oil burned

[b] Source: Telephone survey and compilation by ERCO, 1979.

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EPA-287 (Cin.)
(4-76)

NO_x Removal--

Control Technology Options-- NO_x emissions from steam boilers and in situ combustion can be controlled by the employment of add-on ammonia scrubbers. However, a 20 to 70 percent reduction in the formation of NO_x emissions from surface boilers can be achieved through combustion process changes. The most important process changes applicable to surface steam boilers are:

1. Staged combustion,
2. NH_3 injection, and
3. Catalytic reduction.

At present, only stack gas ammonia scrubbers and catalytic reduction are operational technologies and these techniques still require development. There is skepticism that an NH_3 injection system produced by Exxon will work in the field.

Table 68 summarizes the cost of NO_x removal. Here again insufficient data preempt any attempt at a meaningful analysis of the data. Of particular note is the lack of data for industrial boilers, which are typically smaller than utility boilers and therefore serve to better represent steam-flood boilers.

Particulates--

Control Technology Options-- Particulates produced in the burning of oil are composed primarily of hydrocarbon fractions or have hydrocarbon components, unlike the inorganic ash produced in coal combustion. Oil combustion particulates are fine, are immiscible in water, become sticky as they cool, and are not charged by electrostatic fields. This makes conventional particulate control devices less effective and their maintenance more costly than ash particle control.

However, the technology for the removal of particulates is the most operational for treatment of EOR-associated air emissions. Controls currently employed include:

1. Mechanical collectors (cyclones),
2. Fabric filters (baghouses),
3. Electrostatic precipitators (ESP's),
4. Venturi tubes (wet scrubbers), and
5. Electrified fluidized bed (EFB).

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 68. COSTS OF NO$_x$ REMOVAL AS A FUNCTION OF REMOVAL EFFICIENCY, FUEL TYPE, AND APPLICATION[a,b]

Application	Removal Efficiency		
	0.6 lb/MMBtu	0.3 lb/MMBtu	0.1 lb/MMBtu
Utilities			
Oil			
Capital ($/MMBtu/hr)	24-180[d]	2,900[e]	2,900-3,100[f]
O&M ($/MMBtu/hr)	0.25	>1.6	>1.7
Annualized ($/MMBtu/hr)	0.48	>2.4	>2.5
Coal			
Capital ($/MMBtu/hr)	29-210[f]	3,400[e]	3,500[g]
O&M ($/MMBtu/hr)	0.25	>1.6	>1.7
Annualized ($/MMBtu/hr)	0.52	>2.5	>2.6
Industry			
Oil			
Capital ($/MMBtu/hr)	4.7-11.9[h]	j	j
O&M ($/MMBtu/hr)			
Annualized ($/MMBtu/hr)			
Coal			
Capital ($/MMBtu/hr)	5.7-14.3[i]	j	j
O&M ($/MMBtu/hr)			
Annualized ($/MMBtu/hr)			

Notes to TABLE 68.

[a] All costs in 1977 dollars.

[b] Compiled by ERCO, 1979.

[c] Assuming an average cost of 12.090 Btu/lb coal and 20-24 lbs NO$_x$ produced/ton coal the standards require:

0.6 lbs NO$_x$/MMBtu - 28-30 percent removal
0.6 lbs NO$_x$/MMBtu - 64 percent removal
0.6 lbs NO$_x$/MMBtu - 88 percent removal.

J. David Mobley in "Status of EPA's NO$_x$ Flue Gas Treatment Program," draft paper, EPA, states that combustion modification will reduce NO$_x$ emissions up to 50 percent. Flue gas treatment is necessary for >50 percent removal, and to achieve 90 percent removal both are probably necessary.

[d] "A Program for Reduction of NO$_x$ from Tangential Coal-Fired Boilers Phase IIa," August 1975, EPA. Project Officer, David Lachapelle.

Costs are presented as follows:

O&M	0.21 mills/kWh
Capital	\$0.1-0.4/kW for new units
	\$0.2-1.5/kW for retrofits

in 1975 dollars and for oil-fired units. The costs have been scaled by 0.06 for 1975 and 0.08 for 1976.

[e] Flue gas treatment costs are from "Status of EPA's NO$_x$ Flue Gas Treatment Program," above, where costs in 1978 dollars are:

\$36/kW	Capital
<1.6 mills/kWh	O&M

for 80 percent removal on coal-fired units. Oil-fired units are 17 percent less.

[f] Coal costs are 20 percent higher than oil costs.

[g] Eighty-eight percent removal level requires simultaneous flue gas treatment and combustion modification.

[h] From EPA report, August 1975 cited above, capital cost for combustion modification for a 25 MW unit industrial oil-fired boiler may range from \$4 to \$10/kW in March 1975 dollars.

[i] Capital cost for coal-fired boilers is 20 percent greater than for an oil-fired unit.

[j] Probably higher than utility - to be assessed by Radian, Acurex, and EPA (Radian, 1979).

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Mechanical collectors can be expected to remove large particles from flue gases. However, they tend to be less effective for the smaller particles produced by oil-burning; mechanical removal efficiency is in the 80 percent range.

Fabric filters have a higher removal efficiency, ranging from 95-99 percent. However, the fine sticky particulates tend to clog (bind) the fabric, to cement its surface, and lower the pressure/suction that draws gas through the system. The bags must be cleaned and replaced frequently in order to maintain a high removal efficiency and prevent fire in the apparatus. This maintenance requirement can dramatically increase operational costs.

Electrostatic precipitators also have a relatively high efficiency rate accompanied by high operational costs. As mentioned above, hydrocarbon particles tend to resist the polar charging of electrostatic precipitation because carbon conducts current rather than being caught and removed. This can cause a buildup of hydrocarbons in the ESP and the same problems of clogging (adhering to the walls) and creating a fire hazard unless they are regularly cleaned.

Venturi scrubbers are not useful in hydrocarbon particle removal because these particles are not soluble in water, the principal means of removal being solution in water. However, they may be considered if coal is substituted for oil in steam generation.

Electrified fluidized-bed systems may be the best applied technology for particle removal, although they are a relatively new technology. Because it combines a cyclone for large entering particles with ESP charging and filtering of charged sand particles, removal efficiency is high. However, as a new technology, data on removal efficiency and cost are not available for hydrocarbon particulates.

Efficiency and cost--As a rule, the three particulate removal technologies (dollars/percent removal) can obtain the following removal efficiencies:

Fabric filters	99+ percent
Electrostatic	97 percent
Mechanical collectors	85 percent

Table 69 displays costs typical of the three technologies at the above removal efficiencies. The dramatic increase in costs required to remove fine particulates not collectible by mechanical methods is also illustrated. Table 70 compares the component costs of a range of particulate removal technologies. From the "typical" costs illustrated in Table 69, it is

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 69. EFFICIENCY AND COSTS OF PARTICULATE CONTROL OPTIONS[a] (subject to the various uncertainties noted in the text)

Control Measure	Removal Efficiency (%)	Size (MMBtu/hr)	Cost: Turnkey Capital Cost ($/MMBtu/hr)	Cost: O&M Cost ($/MMBtu)	Cost: Annualized Cost ($/MMBtu)
Fabric Filter	99.7	29	2,300	0.1	1.4
		242	1,200	0.35	0.66
		533	890	0.26	0.49
		708	840	0.25	0.48
Electrostatic precipitator	99.7	145	3,300	0.20	1.0
		436	1,400	0.18	0.54
		708	1,100	0.14	0.41
Mechanical collector		29	990	0.11	0.35
		388	410	0.09	0.20
		708	340	0.08	0.17

[a] Costs developed by ERCO from survey of manufacturers.

possible to estimate the costs of particulate removal per barrel of produced oil. Table 71 outlines these costs and the assumptions used in their estimation. The estimated costs range between $0.03 and $2.50 per barrel of produced oil.

Control of Surface Water Effluent

A variety of control processes exist for complex water effluents. The exact treatment train for a particular application will be dependent upon the dominant pollutants and on the effluent chemistry and specific treatment processes for EOR applications cannot yet be specified. In addition, no analyses of produced water or waste oil streams are available.

Two preliminary flow sheets depicting plausible treatment processes for EOR waste streams which cannot be injected to subsurface formations are presented in Figures 39 and 40. The two processes are a combined biological physical-chemical system and a pure physical-chemical system.

The combined system first removes H_2S and other volatile organics in a stream or air stripping unit. The stripper

PAGE NUMBER
EPA-287 (Cin.) (4-76)

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TABLE 70. APPROXIMATE COSTS OF VARIOUS DUST COLLECTORS TREATING 60,000 cfm OF GASES AT 68° F[a]

Dust Collectors	Efficiency on Standard Dust (%)	Performance Factor[b]	Installed Cost ($)[c]	Pressure Drop in Water	Power Cost[d] ($/yr)	Water Requirements (gal)	Water Cost[e] ($/yr)	Maintenance[f] ($/yr)	Total Operating Costs ($/yr)	Capital Charges[g] ($/yr)	Total Annual Cost ($/yr)	Total Annual Cost (¢/yr/cfm)
Medium-efficiency cyclones	65.3	1.88	11,000	3.7	3,880	-	-	200	[illegible],580	1,100	4,680	7.8
High-efficiency cyclones	84.2	5.35	21,000	4.9	4,520	-	-	200	4,720	2,100	6,820	11.4
Tubular cyclones	93.8	15.1	23,000	4.3	3,960	-	-	200	4,160	2,300	6,460	10.8
Irrigated cyclones	91.0	10.1	26,500	3.9	4,060	4.0	5,280	500	9,840	2,650	12,490	20.8
Low-pressure drop cellular cyclones	74.2	2.88	19,000	1.4	1,310	-	-	200	1,510	1,900	3,410	5.7
Electrostatic precipitators	94.1	15.95	105,000	0.6	1,240	-	-	850	2,090	10,500	12,590	20.0
Irrigated electrostatic precipitators	99.0	99	180,000	0.6	2,240	2.5	3,530	1.350	7,120	18,000	25,120	41.8
Frame-type fabric filters	>99.9	10	60,000	4.0	3,760	-	-	1,100[h]	4,860	6,000	10,860	19.8
Reverse-jet fabric filters	>99.9	10	58,000	5.0	7,980	-	-	950[i]	8,930	5,800	14,830	24.8
Spray towers	96.3	26	62,000	1.4	4,750	3.6	5,280	1,000	11,030	6,200	17,230	28.6
Impingement baffle scrubbers	97.9	46.6	35,000	6.1	5,800	3.0	4,400	1,000	11,200	3,500	14,700	24.5
Inertial orifice scrubbers	93.5	14.4	29,500	6.1	5,640	0.6	880	700	6,220	2,950	9,170	15.3
Venturi scrubbers	99.7	330	51,000	22.0	21,140	7.0	9,680	1,000	31,820	5,100	36,930	60.0
Mechanical scrubbers	98.5	65.6	80,000	-	45,400	5.0	6,800	700	52,900	8,000	60,900	101.5

[a] American Petroleum Institute, 1979.

[b] Efficiency factor = efficiency/(100-efficiency).

[c] Based on Marshall and Stevens Index of 230 and $2.80 per hp; includes cost of fans, pumps, motors, and erection.

[d] Based on $0.01 per kWh.

[e] Based on $0.05 per 1,000 gal.

[f] Estimated as a fraction of installed cost.

[g] Estimated as 10 percent of installed cost.

[h] Includes complete change of bags once annually.

[i] Includes complete change of bags twice annually.

EPA-287 (Cin.)
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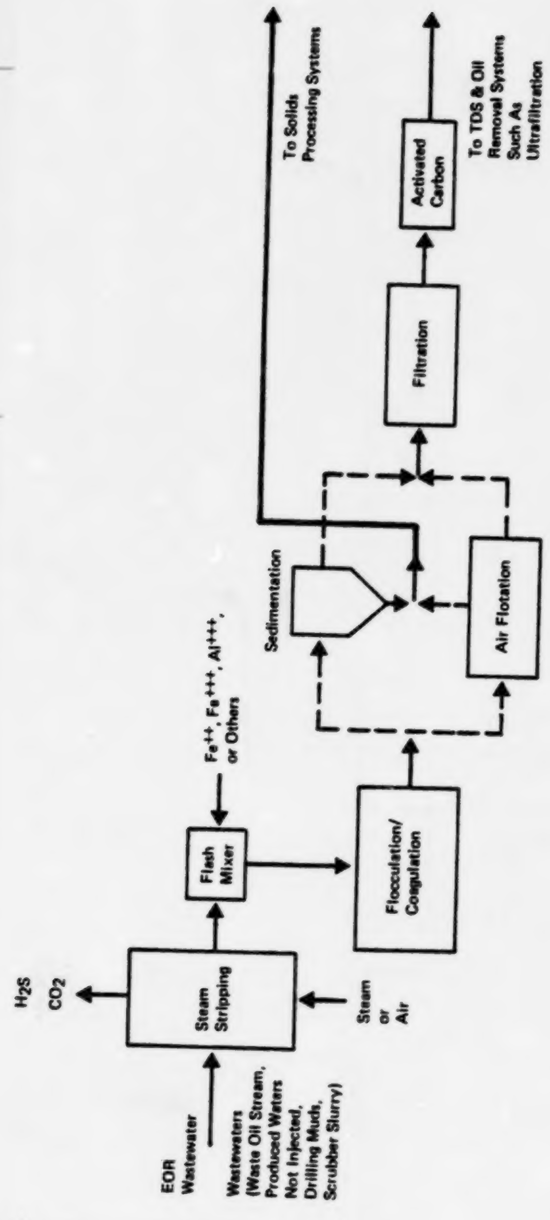
EOR Wastewater
Wastewaters (Waste Oil Stream, Produced Waters Not Injected, Drilling Muds, Scrubber Slurry)
H_2S
CO_2
Steam Stripping
Steam or Air
Flash Mixer
Fe^{++}, Fe^{+++}, Al^{+++}, or Others
Flocculation/Coagulation
Sedimentation
Air Flotation
Filtration
Activated Carbon
To Solids Processing Systems
To TDS & Oil Removal Systems Such As Ultrafiltration

Figure 39. Potential physical chemical treatment system.

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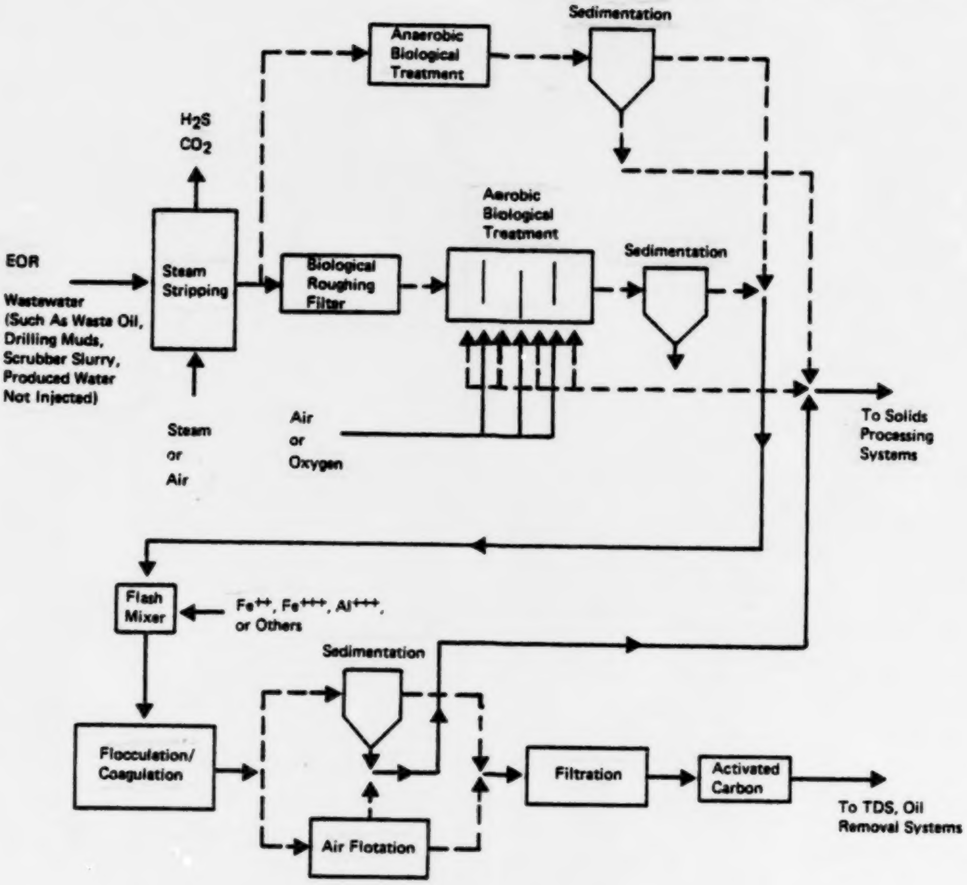
Anaerobic Biological Treatment
Sedimentation
H$_2$S
CO$_2$
EOR
Wastewater (Such As Waste Oil, Drilling Muds, Scrubber Slurry, Produced Water Not Injected)
Steam Stripping
Biological Roughing Filter
Aerobic Biological Treatment
Sedimentation
Steam or Air
Air or Oxygen
To Solids Processing Systems
Flash Mixer
Fe^{++}, Fe^{+++}, Al^{+++}, or Others
Sedimentation
Flocculation/ Coagulation
Air Flotation
Filtration
Activated Carbon
To TDS, Oil Removal Systems

Figure 40. Potential biological physical chemical treatment system.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

TABLE 71. PARTICULATE REMOVAL COSTS FOR STEAM FLOOD EOR[a,b]

	Removal Efficiency (%)	Size (MMBtu/hr)	Cost per bbl Produced Oil ($1977)
Fabric Filter	99.7	29	$2.5
		242	1.2
		533	0.9
		708	0.9
Electrostatic precipitators	99.7	145	1.8
		436	1.0
		708	0.7
Mechanical collectors	Not efficient in removing fine particulates	29	0.6
		388	0.4
		708	0.3

[a] Assuming that 3.5 bbl of oil are produced per bbl oil burned, and that 6.5 x 10^6 Btu energy is one bbl oil.

[b] Derived from Table 68 using above assumptions.

effluent is probably suitable for anaerobic treatment directly but a biological roughing filter, such as a trickling filter, should precede any aerobic system. The biological processes will reduce polymers, volatile compounds, other organics, BOD, and COD. Chemical treatment followed by either flotation or sedimentation will remove suspended material, metals and organics. Flotation will remove suspended material, metals and polymers, and other organics. Filtration will remove any of the chemical floc that usually carries over from a sedimentation unit. Activated carbon will remove residual organics and make the water suitable for use in one of the membrane processes. Finally, processes such as neutralization and ion exchange may be required to eliminate particular polymers or improve process efficiency.

In the pure physical-chemical (P-C) treatment system, the units will have to have a larger capacity, and reduction of polymers, BOD, COD, and volatile acids will depend on the effectiveness of the coagulants combining all the material in the water and being efficiently removed in the sedimentation or flotation process. The pH of the process stream may have to be adjusted to improve the efficiency of the system.

EPA-287 (Cin.)
(4-76)

The various treatment processes likely to be considered for use in the EOR application are briefly described below.

Coagulation/Flocculation and Sedimentation--

These processes involve the addition of chemicals to the waste stream followed by gentle stirring to effect the aggregation of colloidal particles. A quiescent zone allows the agglomerated particles to settle from the wastewater. The primary inorganic chemicals used in coagulaton/flocculation and sedimentation processes are lime, and aluminum and iron salts.

Oxidation and Reduction--

These processes convert undesirable chemical species to species that are neither harmful nor objectionable. The primary substances of concern in produced water, which can be treated by these processes, include Mn^{+2}, Fe^{+2}, S^{-2}, CN^{-}, SO_3^{-2}, phenols, amines, and other organics that are toxic or impart a color, taste, or odor to the water. Since it is desirable to limit the amount of oxidizing agent residue remaining in the water, there are only a few substances that are currently used to any degree: air, oxygen, ozone, hydrogen peroxide, potassium permanganate, chlorine, hypochlorites, and chlorine dioxide.

These processes would be most effective in removing CN^{-} and S^{-}. If ozone is used, polynuclear aromatic hydrocarbons will be reduced.

Neutralization--

Acid addition will reduce the carbonate alkalinity of the wastewater and change the balance of the various ionic species in the wastewater. Addition of CO_2 would not reduce the alkalinity of the stream. Neutralization may be necessary if membrane treatment (reverse osmosis or ultrafiltration) of the wastewater is contemplated.

Activated Sludge--

The biological treatment process involves aerating the wastewater in an aeration basin and removing the solids in a sedimentation unit. A portion of the settled sludge is recycled to the aeration basin to facilitate aerobic decomposition and improve the removal efficiency of BOD, COD, and other parameters. The remainder of the sludge is removed for stabilization and final disposal.

The principal constituents removed by activated sludge will be BOD, COD, polysaccharides, suspended solids, oil, grease, phenols, metals, and volatile acids. Reduction of cyanide and other trace constitutents will also occur.

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Anaerobic Digestion-Fermentation--

This process involves the treatment of wastewater by biological organisms in the absence of oxygen and is normally used for stabilizing biological sludges and treating concentrated wastes. Anaerobic treatment is sometimes favored as a biological treatment process because it can handle heavy organic loadings such as polymers and oils without upsets, requires minimal land area, has minimal power costs since no aeration is required, generates a low amount of solids, and produces a methane that can be used as a source of power in the treatment process. Anaerobic processes have lower nutrient requirements than aerobic processes and are more suitable for seasonal loadings. A fairly new development in anaerobic treatment is the anaerobic filter. There are only three installations in the United States at the present time but all the systems are operating quite well on fairly heavy organic waste loadings (Brown and Caldwell, 1978).

The primary constituents removed will be BOD, COD, volatile acids and suspended solids. Ammonia and H_2S should be removed prior to anaerobic treatment. Methane gas is produced and can be used as a heat source or for fuel in the treatment process.

Physical Stripping--

There are many stripping methods in use, but they usually involve the downward flow of water through a tower filled with trays or packing media while an ascending flow of gas removes H_2S, NH_3, CO_2, and other volatile substances. The stripping gas can be steam, air, flue gas, or some type of fuel gas. When stripping is used in municipal wastewater treatment systems to remove ammonia from solution, air is usually used and this system is optimized by operating in the pH range of 11.

However, when NH_3 and H_2S are present in aqueous solutions they combine to form the salt NH_4SH. The hydrolysis constant of this reaction increases as the temperature of the solution increases, thus more free NH_3 and H_2S are present in warmer solutions and stripping efficiencies increase with increasing temperatures.

H_2S, NH_3, CO_2 and other volatile compounds will be removed. There will also be incidental stripping of some phenols and other organics.

Ion Exchange--

This is a process by which ions are displaced from an insoluble exchange material by ions of a different species in solution. Natural and synthetic ion exchange resins are available but synthetic resins are more widely used because of their durability. Clinoptilite (a natural resin) is used in the removal of ammonia from wastewater. This system is popular

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

because the clinoptilite can be regenerated by using lime, and the ammonia can be easily stripped from the lime solution. However, calcium carbonate is deposited on in the piping flow system, which is a drawback.

A serious problem with the use of the ion exchange process for wastewater treatment is the binding of the resins caused by residual organic matter found in the process stream. Generally, ion exchange is used as a polishing process and is preceded by filters or scavenger exchange resins.

Although the high alkalinities and organic content of the EOR wastewaters would tend to preclude ion exchange, a recent study has shown that ammonia and bicarbonate could be removed economically with synthetic weak acid cation exchange resins if regeneration of the resin with CO_2 (generated on-site) can be technically accomplished.

Ion exchange units would be primarily used to remove NH_4^+, bicarbonate alkalinity, Ca^{++}, and Mg^{++} and NO_3^-, and other metals.

Electrodialysis (ED)--

Dissolved solids are held in a wastewater by electrochemical force that bonds oppositely-charged ions. In the ED process (see Figure 41), wastewater flows between alternatively placed, semipermeable membranes that permit the passage of either cations (C) or anions (A). The alternative cation-permeable and anion-permeable membranes are separated by spaces that direct the flow of water and combine to form a membrane stack. Two metal electrodes connected to a direct current source are used to supply the electric energy for dialysis. When DC voltage is applied across the stack, the ions are polarized and each is attracted toward the electrode of the opposite charge. The cation-permeable membranes allow only positive ions to pass through; the anion-permeable membranes, only negative ions. In alternating compartments, one stream is diluted (the product water), the other concentrated (the wastewater). Unlike the reverse osmosis process, in the ED process the dissolved solids from the wastewater stream pass through the semipermeable membranes and the dilute or field water is left behind. All pollutants that do not ionize upon the application of DC current cannot therefore be separated from the waste stream by the ED process. These pollutants include all suspended matter such as sand, silt, organics, and others.

The percentage of dissolved solids (sulfates, chlorides, nitrates, and sodium) removal achieved by the ED process is approximately proportional to the current density and membrane area. Since the current density can be easily controlled, the degree of dissolved solids removal can be tailored to the economics of a given application. The work energy required

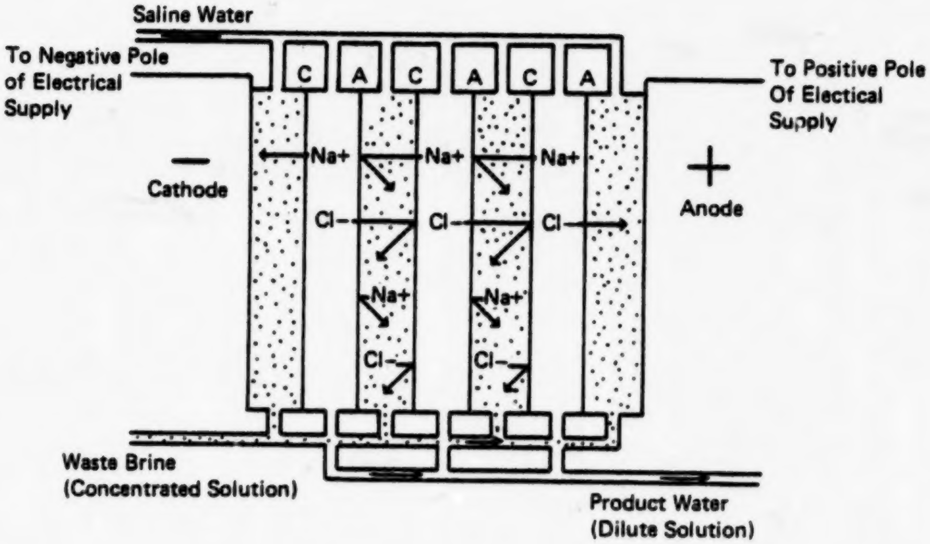
Saline Water
To Negative Pole of Electrical Supply
C
A
C
A
C
A
To Positive Pole Of Electical Supply
—
Cathode
Na+
Na+
Na+
Cl−
Cl−
Cl−
+
Anode
Na+
Na+
Cl−
Cl−
Waste Brine (Concentrated Solution)
Product Water (Dilute Solution)

Figure 41. An electrodialysis membrane illustrating the process of NaCL removal from feed saline water.

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUS-TRATIONS

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

depends on the degree of ionization of the dissolved solids and the temperature of the feedwater. Most ED systems now require 0.4 kWh of energy/1,000 gallons of product water for every 100 ppm of dissolved salts removed from the solution (plus 2 kWh/1,000 gallons for pumping). When compared to reverse osmosis (RO) energy requirements, the ED process is more energy efficient for TDS feed solutions up to about 10,000 ppm. The ED process for higher feedwater concentrations is still in the developing stages. With these considerations alone, it seems that ED systems would be economically feasible for feed water TDS concentrations on the order of 30,000 ppm.

Preheating the feedwater in the ED process increases its ionization level and electrical conductivity and thus facilitates removal of the dissolved solids. Temperatures higher than 100° F, however, can irreparably damage the membranes by causing growth of bacteria and algae, which form slime deposits in filter pores, pipes, bends, etc. Although increasing the number of stages in the ED process is an alternative to such preheating, this method also increases the electrical energy costs. Chemical pretreatment is used for a number of purposes, for example, to remove alkalinity sulfuric acid is added. Such acid treatment of feedwater may be necessary to retard formation of carbonate scales in the membranes, although scaling is less of a problem in ED than in RO. Biological fouling is controlled by addition of chlorine; however, more than 0.1 ppm of residual chlorine will damage the membranes. The level of iron and manganese in the feedwater should be maintained at less than 1.2 ppm. Filtration and clarification is also necessary to maintain the turbidity of the filtered stream at less than 5 Formazian turbidity units (FTU).

The membranes typically used for the ED process have a relatively long service life and the membrane surfaces are readily accessible for cleaning. Self-cleaning can be accomplished by reversing the direction of the current, which in turn reverses the direction of polarity across the cell.

Reverse Osmosis (RO)--

Reverse osmosis is increasingly being used to recover pure water from wastewater sources. Figure 42 contrasts reverse and direct osmosis. Figure 42(a) shows two chambers, separated by a semipermeable membrane, which were initially filled to the same level with pure water and wastewater respectively. The osmotic pressure is higher in the pure water chamber since the dissolved solids in the wastewater tend to lower the osmotic pressure of that solution. The semipermeable membrane theoretically allows pure water (but not solids) to pass in either liquids in the two chambers causes the pure water to permeate into the wastewater chamber and thus change the water levels on the two sides of the membrane as indicated. If, as shown in Figure 42(b), the wastewater chamber is subjected to a pressure

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PAGE NUMBER
EPA-287 (Cin.)
(4-76)

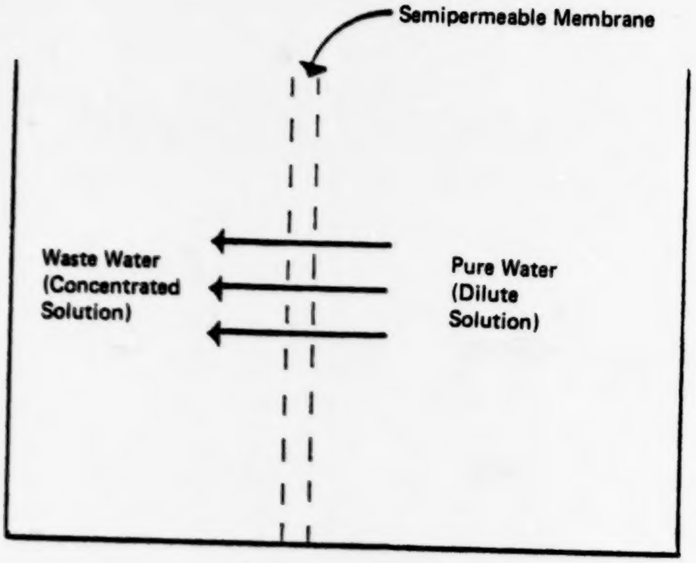
Semipermeable Membrane
Waste Water (Concentrated Solution)
Pure Water (Dilute Solution)

Figure 42a. Direct osmosis.

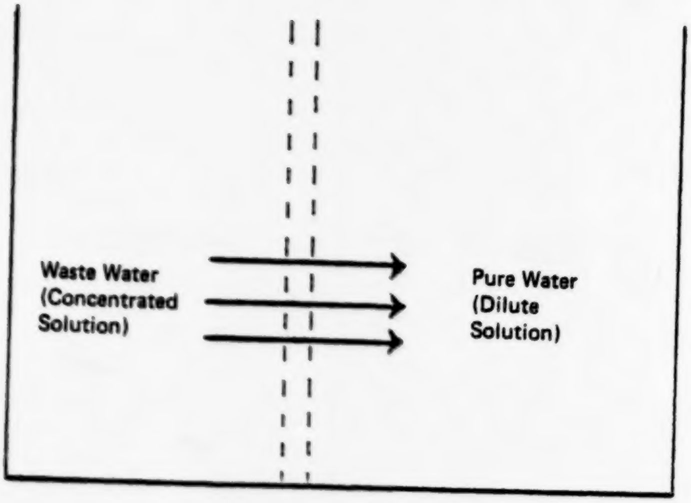
Waste Water (Concentrated Solution)
Pure Water (Dilute Solution)

Figure 42b. Reverse osmosis.

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BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

that is greater than the difference between the osmotic pressures, the direct osmosis process just described is reversed, and pure water is forced out of the wastewater chamber, rendering the wastewater more concentrated. The reverse osmosis systems are most commonly used for the removal of dissolved solids, such as sulfates, chlorides, nitrates, and sodium, from feedwater solutions.

The presence of oxygen, organics, and turbidity in feed water is undesirable in reverse osmosis systems since these elements favor biological fouling and membrane compaction, and thus adversely affect membrane permeation rates and service life. Therefore, chemical pretreatment of feedwater may be needed to control or prevent these effects. Biological fouling is controlled by the addition of chlorine to feedwater; to avoid membrane damage, the amount of surplus chlorine is usually maintained at less than a specified limit that is dependent upon the membrane material. The turbidity of feedwater, controlled through the use of filters, should be relatively low in reverse osmosis systems, between 0.1 and 0.2 FTU. Carbonate scales that cause membrane compaction are prevented by making the feedwater somewhat acidic (pH = 5-6). Water pretreatment (including filtration and clarification) is critical in RO systems and the degree of pretreatment should be assessed from an economic point of view in the design of this type of water purification plant.

Reverse osmosis membranes are commercially available in tubular, plate and frame, hollow fiber, and spiral wound configurations. Of the membrane types currently receiving the most attention, the cellulose triacetate (hollow fiber) and poly (ether/amide) thin-film composite (spiral-wound) membrane systems are the most advanced. The freshwater production rate is a function of operating pressure. Typically a cellulose triacetate membrane, when used with a feedwater pressure of 800 psi, will yield a pure water flux of 2 to 3 gfd (gallons per square foot of membrane area per day). The corresponding dissolved solids rejection efficiency is over 99 percent. With a poly (ether/amide) thin-film composite membrane system and an operating pressure of 1,000 psi, the product water flux is about 10-12 gfd and has a corresponding rejection efficiency of over 99 percent. The feedwater total dissolved solids concentration (TDS) for these cases is 35,000 ppm. Spiral wound membranes are generally less sensitive to plugging than the hollow fiber type of membranes. Therefore, these latter systems require more elaborate filtration of feedwater than the spiral wound ones. Spiral wound systems have exhibited satisfactory performance with feedwater temperatures up to 100° F, while the recommended upper limit for hollow fiber membranes is 95° F.

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

Activated Carbon--

Adsorption of organic compounds by activated carbon involves the accumulation or concentration of substances at a surface or interface. Adsorption is a process in which matter is extracted from one phase and concentrated at the surface of another. Adsorption onto activated carbon can occur as a result of:

- The low solubility of a particular solute in the waste water
- The high affinity of a particular solute in the waste water for activated carbon

There are essentially three consecutive steps in the adsorption of dissolved materials in waste water by activated carbon:

1. Transport of the solute through a surface film to the exterior of the carbon
2. The diffusion of the solute within the pores of the activated carbon
3. Adsorption of the solute on the interior surface of the activated carbon

Adsorption is a surface phenomenon, and the ability of activated carbon to adsorb large quantities of organic molecules from solution stems from its extremely large surface area.

A recent project completed by the MERL Division of EPA uncovered the following compounds whose concentrations were not significantly reduced by activated carbon adsorption:

- Acetone cyanohydrin
- Butylamine
- Choline chloride
- Cyclohexylamine
- Diethyleneglycol
- Ethylenediamine
- Hexamethylenediamene
- Morpholine
- Triethanolamine

In addition to these compounds 61 other compounds were examined. Adsorption capacities ranged from 360 mg of chemical adsorbed per gram of carbon for hexachlorobutadiene to 0.70 mg/gram for benzene. The results of this work demonstrate that activated carbon can remove some organics very efficiently

EPA-287 (Cin.)
(4-76)

but cannot be expected to efficiently remove all the organics in the waste stream.

While activated carbon does not remove every organic compound it is probably the best available "broad spectrum" process. If there are numerous organic compounds in a waste stream, carbon adsorption is a process that should be attempted. Carbon has been used in industrial water and wastewater treatment, municipal wastewater treatment, and is currently the subject of intense study for drinking water treatment. Since regulations are being developed based on specific organic contaminants and since EOR can result in significant concentrations of organics, carbon adsorption is a process that deserves careful study.

Filtration--

Conventional Filtration--Primary removal is directed to suspended solids although reductions of organics, BOD, COD and TOC will also occur. This process is usually used as a polishing step either to prepare wastewater for subsequent treatment processes or to remove some residual suspended material remaining after sedimentation. Recently the use of dual-media and multimedia filters has allowed for longer filter runs by inhibiting plugging of the bed. The media can be composed of sand with different grain size or of different types of sand or of sand and another material such as anthracite or activated carbon. Because of the high amount of organics in EOR wastewater, filtration would probably be used after the major treatment steps such as: chemical treatment and sedimentation; biological treatment and sedimentation; dissolved air flotation; and prior to subsequent polishing steps such as activated carbon, ion exchange, electrodialysis or reverse osmosis.

Ultrafiltration--This process consists of membranes with pore sizes about 1,000 times smaller than ordinary filters. Thus, with this process not only all the suspended matter in the wastewater stream can be removed, but also filtration can be performed at the molecular level. However, dissolved solids of molecular weights below about 2,000 cannot ordinarily be removed by ultrafiltration processes. Typically, ultrafiltration pores range from 1 nm to 10 nm.[54] The sizes of bacteria range from 5 to 10 nm and are therefore readily rejected by ultrafiltration. Most viruses and proteins are also rejected by this process. Sugar and water, whose sizes are on the order of 0.5 nm and 0.2 nm respectively, are small enough to pass through the ultrafiltration membranes, however. For the removal of dissolved solids like sulfates, chlorides, nitrates, and sodium, other means of separation, such as reverse osmosis, electrodialysis and distillation, are required. In ordinary ultrafiltration systems applied pressures of up to

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[54] 1 nm = 10^{-9} meter = 10^{-3} micron (μ)

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3/8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

50 psi are quite common and in most cases the municipal supply pressure is adequate for this process. In ordinary filtration the fine particles tend to clog the filtering media, thus causing compaction because of decreased filtration efficiency. In ultrafiltration processes, on the other hand, the feed water stream is continuously passed over the filter surface, rendering the medium less susceptible to compaction due to increased turbulence in the flow channels. Like RO membranes, the UF membranes are commonly available in the hollow fiber and spiral wound configurations. The hollow fiber type of membranes are more susceptible to compaction and may require a prior filtration stage for an economically feasible UF scheme.

Air Flotation--

Solids and colloidal suspensions will be removed in the air flotation process. Incidental removal of organics, phenols, TOC, BOD, COD, and metals will also occur. This process is used to separate particulates from a liquid phase. Separation occurs by introducing fine bubbles into the liquid phase. The bubbles attach to the particulate matter and the resultant buoyancy causes the particles to rise. Flotation can be used to remove particulate matter or to concentrate sludges. The greatest advantage of this system is that it is very effective in the removal of very small, light particles that would settle very slowly in a sedimentation process. There are three main types of flotation systems: air flotation (AF), dissolved air flotation (DAF), and vacuum flotation (VF). AF and VF units are used primarily for floating grease and scum forming substances and thus are probably not appropriate for treating oil waste waters. DAF is used for treating industrial wastes and for concentrating sludges, and thus could be appropriate either for treating the waste water or to serve as a solids processing step. Thus, DAF is the flotation process most likely to be used in treating EOR waste water. Chemicals are usually added to condition the water prior to flotation. Organic polyelectrolytes and inorganic chemicals such as aluminum and ferric salts bind the particles together and increase the removal efficiency.

Centrifugation--

This is a classifying process that is widely used in industry for separating liquids of different density, for thickening slurries, or for removal of solids. The process is being used for dewatering sewage sludges in the United States. Pretreatment of the sludge with chemical conditioning agents is usually required to prevent very fine, low density solids from remaining in the centrate.

Because of the variability of sludges, most centrifuge operations are pilot tested to determine their effectiveness prior to selection. Centrifugation is a potential method for dewatering the biological or chemical sludges that would be

EPA-287 (Cin.)
(4-76)

produced in the oil shale retort wastewater treatment system. Centrifugation might also be effective in breaking oil-water emulsions in the wastewater.

Vacuum Filtration--

This process is probably the most widely used method of dewatering sludge by mechanical means. Vacuum filters have been used in dewatering primary, secondary, and chemical sludges for final disposal or as a pretreatment step for incineration. Solids content in sludge from a vacuum filter is typically in the range of 20 to 30 percent although solids content of 30 to 40 percent can be achieved.

Methods for Control of Groundwater Pollution--

Deep groundwater pollution resulting from enhanced recovery can be expected mainly as a result of migration of reservoir fluids from nonisolated injection zones to neighboring high permeability zones and as a result of well casing leaks and travel along the outsides of improperly placed casings. Shallow groundwater pollution may be expected from surface spills of hydrocarbon, from solid waste leachate, and from ponded drilling muds.

The leachate control problem has been the subject of numerous detailed research efforts. For further discussion of other EPA research in the area the reader is referred to studies being sponsored by EPA, RTP; and EPA-IERL studies.[55] A variety of options applicable to enhanced recovery exist, including specially designed disposal pit liners, special containment vessels for concentrated hazardous solid wastes, and careful location of solid wastes disposal sites to take advantage of natural geologic fields.

Groundwater contamination resulting from surface hydrocarbon spills is another control problem that has been researched in detail. The reader is referred to studies being carried out by the EPA Oil Spill Research Unit in Edison, New Jersey (for example, Trentachofte et al., 1979). A variety of methods exists for minimizing the probability of spills and their subsequent impact, including diking around storage tanks, inspection and maintenance of transport lines, and spill response contingency plans.

Control of Well Casing Problems--

Problems with well casings or perforations commonly result in groundwater contamination. Well shafts provide the easiest route for groundwater contamination since they provide communication between all subsurface formations to a given depth. Common types of casing problems include well casing cracks, improperly sealed casings, and improperly placed perforations.

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[55] Currently in a design phase.

The causes of these problems include structural problems with the casing material, the corrosive action of injection fluids on components of the crude, the use of aging wells, and incorrect drilling and completion practices.

Elimination of these cause of groundwater contamination can be approached by the following measures:

- General attention to best engineering practices. These measures can be expected to be closely followed at present since they are consistent with maximizing production yield and minimizing chemical loss.
- Reworking old wells. When enhanced recovery projects are started in old fields using old wells, all wells should be reworked to avoid leaks due to aging of the wells. In ongoing projects, wells subject to corrosion may also require reworking. Consistent standards exist for the construction of well casings and for the cementing of old wells. In many cases, particularly for small fields run by independent operators, well casings and old well cementings are carried out with more consideration for minimizing construction costs than for insuring the stability of the wells. Specific standards for enhanced oil recovery projects that are backed up by compliance inspections would result in a consistent quality for wells in enhanced oil recovery fields.
- Monitoring of downhole pressure with quick response plan ready. When pressure is continually monitored, well problems can usually be flagged early enough to allow simple repairs rather than major reworkings.
- Periodic casing check and tube replacements. Many of the well fields in which enhanced recovery techniques are used are populated with a number of old wells that may contain structural weaknesses due to their age and the brines which come in contact with the metal and concrete surfaces. Programs involving the inspections of these old wells and repair of these wells on a regular basis would reduce the chances of contamination events resulting from old well failures.
- Injection at reduced pressure. This option involves reduction in the injection pressure during the waterflooding stage of a recovery project. High injection pressures can induce well problems such as fracturing of the subsurface strata allowing movement of hazardous chemicals out of the oil reservoir. Injection at reduced pressure, when it can be applied without impacting the effectiveness of the recovery technology, can reduce the opportunity for such contamination to occur.

- Control sulfate reducing bacteria. Use of biocides to control bacterial action can help control the formation of corrosives in the crude oil. To date, the available biocides are of limited effectiveness. In particular, the injected biocides can only be transported for limited distances in the reservoir. Development of other bacterial controls is of importance both for pollution control and for quality of the produced crude.

Migration of Reservoir Fluids to Neighboring High Permeability Zones--

Groundwater pollution resulting from subsurface flow is known to be a problem but little data are available, hence a program of specific controls is difficult to formulate. One currently available method of control is injection of cross-linking polymers into suspected regions of fluid flow out of the reservoir. The polymers link within the reservoir to form a block against continued flow. Various patented cross-linking polymer injection procedures are held by the oil companies.

INTERMEDIA TRADEOFFS AND TECHNOLOGY OPTIONS

The selection of an enhanced recovery technology for a particular field involves a variety of technological and environmental constraints. Where several technologies may be expected to successfully recover remaining oil in place, that is, meet technological constraints, then environmental hazards become a factor to be taken into account in selecting the enhanced recovery program.

Technology Options

The selection of the best technology(ies) for a given pay zone is still not subject to a clear set of quantitative rules. Test and pilot project results are continually resulting in changes in thinking regarding recovery methods. Tables 72 through 75 summarize four different sets of technical screening criteria that have been developed. These show considerable overlap, that is, various reservoir types are conducive to the application of several technologies. Thus, within a given general category, there are a variety of options available regarding which specific chemicals are to be injected into the pay zone.

Intermedia Tradeoffs

The environmental constraints that should be considered in selecting between several possible EOR/EGR programs at a field must be developed in detail for each site being evaluated. Based on the previous sections of this report we have developed a summary table which presents the general tradeoffs that exist (Table 76).

EPA-287 (Cin.)
(4-76)

TABLE 72. NATIONAL PETROLEUM COUNCIL SCREENING CRITERIA[a]

Screening Parameters	Units	Chemical Flooding Processes			Miscible Process	Thermal Processes	
		Surfactant	Polymer	Alkaline	Carbon Dioxide	Steam	In Situ Combustion
Oil gravity	°API	>25	-	<35[b]	>27[c]	<25	<25
Oil viscosity (μ)	cp	<30[b,c]	<200	<200	<10	>20	>20
Depth (D)	Feet	-[c]	-	-	>2,300[b]	>200 <5,000[b]	>5,000
Zone thickness (h)	Feet	-	-	-	-	>20	>10
Temperature	°F	<250	<200	<200	<250[b]	-	-
Permeability, average ($\bar{K}$)	md	>20[c]	-	-	-	-	-
Transmissibility (Kh/μ)	md-ft/cp	-	-	-	-	100	20
Salinity of formation brine (TDS)	ppm	<200,000	-[b]	-[b]	-	-	-

[a] NPC, 1976.

[b] See text of appropriate appendix.

[c] Used to estimate required well spacing for given project life.

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EPA-287 (Cin.)
(4-76)

TABLE 72 (Cont.)

Screening Parameters	Units	Chemical Flooding Processes			Miscible Process	Thermal Processes	
		Surfactant	Polymer	Alkaline	Carbon Dioxide	Steam	In Situ Combustion
Minimum oil saturation at start of process							
In water-swept zones (S_{orw})	fraction	>20[b]	-	-	-	-	-
Mobile $(S_{or}S_{orw})$	fraction	-	>0.10	-	-	-	-
Minimum oil content at start of process (S_{or})	B/AF	-	-	-	-	<500	>500
Rock type	-	sandstone	-	sandstone	sandstone or carbonate	sandstone or carbonate	sandstone
Other	-	d	d	d	d	d	d

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[d] Other criteria including geological data were also considered. The specific criteria used depended upon the process. In general, reservoirs with continuous and uniform strata were ranked higher than were heterogeneous reservoirs with extensive faulting, discontinuous lens-type deposits, fractures, etc. Similarly, reservoirs with extensive underlying aquifers of overlying gas caps were ranked lower or excluded as EOR candidates in view of the decreased likelihood of a successful EOR project.

TABLE 73. OFFICE OF TECHNOLOGY ASSESSMENT SCREENING CRITERIA[a,b]

	Process				
Property	Carbon Dioxide Miscible	Steam Drive	In Situ Com- bustion	Surfactant/Polymer	Polymer
Oil gravity, (°API)	-	-	≤45		
Oil viscosity (cp)	≤12	-	-	1976 ≤10 1980 ≤20 1995 ≤30	≤200
Depth (ft)	≤27° API, <7,200 27°-30°, >5,500 ≥30°, ≥2,500 Depth correlated to miscibility pressure (Temp. correction also applied - see Appendix B)	>500 <5,000	<500		
Temperature (°F)		-		1976 ≤120 1980 ≤170 1985 ≤200 1990 ≤225 1995 ≤250	1976 ≤120 1980 ≤170 1985 ≤200 1990 ≤225 1995 ≤250
Permeability (mD)		-		≥20	≥20
Transmis- sibility (mD-ft/cp)		≥100	≤20		
Salinity of brine[c] (TDS, ppm)	- -	- -	- -	- ≤200,000	-
Rock type		-	sandstone	sandstone	-

[a] OTA, 1978

[b] For all processes - Gas Cap Reservoir - Considered applicable for EOR processes if a waterflood had been carried out or was in progress. If an EOR test or process is in progress, then the reservoir is considered to qualify for that process.

[c] Insufficient information to screen on this variable.

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EPA-287 (Cin.)
(4-76)

TABLE 74. LEWIN AND ASSOCIATES SCREENING CRITERIA

Screening Parameters	Steam Drive	In Situ Combustion	CO_2 Miscible	Micellar/ Polymer	Improved Waterflood
Viscosity - centipore (cp) at reservoir conditions	NC[a]	NC	<20	<20	<200
Gravity (°API)					
(Other than California crudes)	>10	(10-45)	>30	>28	>18
(California crudes)	(>10)	(10-45)	(>26)	(>25)	(>16)
Fraction of oil remaining in area to be flooded (before EOR) - %PV	50[b]	50[b]	25	25	25
Oil concentration (B/AF) Porosity x oil saturation	<500 >0.065	>400 >0.05	NC	NC	NC
Depth (feet)	<5,000[c]	>500	>3,000	C - (8,500)[c,e]	NC - (8,500)[c,e]
Temperature (°F)	NC	NC	NC	<200[e]	<200[e]
Original bottom hole pressure (psi)	NC	NC	>1,500	NC	NC
Net pay thickness (feet)	>20	>10	NC	NC	NC
Permeability - millidarcy (mD)	NC	NC	NC	>20 (with polymer drive)	>20

[a] NC - not a critical factor.

[b] In portion of field to be flooded. Assuming 80 percent of area of reservoir contains 95 percent of remaining oil, the oil saturation for the total field becomes 42 percent of pore volume.

[c] Depth at which the temperature constraint of 200° F will be reached.

[d] These criteria apply to reservoirs with substantial remaining primary recovery.

[e] Using current technology.

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EPA-287 (Cin.)
(4-76)

TABLE 74. (Cont.)

Screening Parameters	Steam Drive	In Situ Combustion	CO_2 Miscible	Micellar/ Polymer	Improved Waterflood
Transmissibility (permeability x thickness/viscosity)	>100	>20	NC	NC	NC
Natural water drive[d]	none to weak	none to weak	none to weak	none to weak	none to weak
Gas cap[d]	none to minor	none to minor	none to minor	none to minor	none to minor
Fractures	NC unless extreme	none to minor	none to minor	none to minor	none to minor
Lithology	NC	NC	NC	sandstone only[e]	NC
Salinity - parts per million (ppm) TDS	NC	NC	NC	<50,000[e]	NC
Hardness (ppm) calcium and magnesium	NC	NC	NC	<1,000[e]	NC
Comments	porosity x thickness (high) 10-acre spacing Economic fuel available High net to gross pay Low clay content	high dip preferred Porosity x thickness high Low vertical permeability preferred Preferred temperature >150 High net to gross pay	Thin pay preferred High dip preferred Homogeneous formation preferred Porosity x thickness low Natural CO_2 availability Low vertical permeability in horizontal reservoirs	Homogeneous formation preferred Low clay content Porosity x thickness (high) Prefer waterflood sweep 50%	Use with or prior to waterflood Low calcium and clay content Porosity x thickness (high)

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(4-76)

TABLE 75. GULF UNIVERSITIES RESEARCH CONSORTIUM SCREENING CRITERIA

Term	Units	Surfactant/ Micellar	Carbon Dioxide Miscible	Polymer	Steam Drive	In Situ Combustion
Oil gravity	°API	>25	>30	>20	10–25	10–35
Depth	Feet		>2,000		<3,500	>300
Temperature	°F	<175		<225	NA	NA
Thickness	Feet	>10	>10	>5	>20	>10
Oil Sat. (S_o)	%PV	>20	>20	$>S_{or}$	See $ØS_o$	See $ØS_o$
$ØS_o$	Frac.			See S_o	>0.09	>0.09
	bbl/AF				>700	>700
Permeability	Millidarcies	>50		25–1,500	>100	>100

EPA-287 (Cin.)
(4-76)

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EPA-287 (Cin.)
(4-76)

TABLE 76. SUMMARY OF ENVIRONMENTAL TRADEOFFS

Type of Environmental Degradation	Major Technologies Contributing Pollutants[a]	Intermedia Impacts of Controls	Regional Considerations
Noise	Drilling and construction required for all technologies	None	Not a significant problem in remote areas
Air	Steam drive, steam soak, in situ combustion	Scrubber slurry water, scrubber sludges	Strictest controls in California and Colorado
Solid wastes	Small amounts of solid wastes from all technologies	Air emissions from incineration or gasification	Of concern in all regions
Surface water	Hydraulic fracturing	Solid wastes from wastewater treatment	Of concern in all regions
Groundwater	All technologies	Some control options involving surface treatment and discharge generate surface water effluents and sludge	Of concern in all regions. Of particular importance when projects occur in the vicinity of freshwater aquifers used for water supply
Water consumption	Waterflooding, polymer flooding, alkaline flooding	Water treatment sludges and surface water effluents	Mainly a concern in states west of the Mississippi and locales with "sole-source" aquifers[b]

[a] All EOR and EGR technologies contribute some of each pollutant.

[b] Sole-source aquifers as designated by EPA.

SECTION 6

NEEDS FOR FURTHER STUDY

This final section of the report discusses the major areas of data gathering and methodology development that are needed. The assembly of these data would allow a more definitive assessment of the pollutants being generated. These data are also needed to enable the comparative analysis of levels of benefits that would be obtained from the implementation of different options for pollution control.

The ultimate goal of this area of research is to provide an assessment of the major areas of environmental concern and optimal design of control systems. To this end, methodologies and data need to be developed for the performance of cost-benefit analyses. These cost-benefit analyses can then be useful in outlining pollution control strategies and scenarios designed to: (1) minimize costs but still meet current regulations, (2) minimize hazardous pollutant levels in various media, and (3) minimize costs to the industry per barrel of oil produced given recognized and documented environmental constraints.

The first part of this section discusses the major remaining uncertainties regarding impacts of enhanced recovery operations. The next part discusses proposed monitoring activities which would provide periodic data on various parameters key to the measurement of environmental degradation of enhanced recovery. The final part discusses the highest priority research needs.

MAJOR UNCERTAINTIES REGARDING IMPACT

A number of data critical to the environmental assessment of EOR are not available at this time. In Section Four summary flow sheets were presented for each of the enhanced recovery processes. Each of the circles in those flow sheets represent potential pollutant sources. Many of the potential pollutant sources identified by the process flows are not characterized in this report because of a lack of necessary information. The major types of information gaps that prevent Section Four of the report from being a complete pollution assessment are as follows:

1. Health risks of chemicals. Most of the chemicals to be employed in enhanced recovery operations do not appear on the various lists of chemicals that have been or are being studied by the EPA. Thus, toxicological data need to be developed for many of these chemicals.

   The data needs include: (a) Bacterial screens - Bacterial tests to screen for mutagenicity/ carcinogenicity have been carried out for only a handful of enhanced recovery process chemicals. These tests, which represent a relatively inexpensive means for toxicological data assembly, should be carried out for all enhanced recovery process chemicals. (b) Carcinogenicity and toxicity tests using rats and other mammals - Such toxicological data should be developed for those chemicals identified by the bacterial screens to be of concern and that are used in significant quantities and processes. (c) Aquatic toxicity bioassays - Aquatic toxicity bioassays should be carried out at a range of concentrations for those enhanced recovery chemicals that have the potential to appear in surface water bodies. (d) Plant bioassays - Plant bioassays should be carried out on those enhanced recovery chemicals or residues that are candidates for land application or surface disposal (for example, enhanced gas recovery wastewater).

2. Groundwater seepage. Further information is required on the persistence and dispersion of injected chemicals over time, transport mechanisms out of reservoirs, and movement of these chemicals in freshwater aquifers. Almost nothing is known about contamination by enhanced recovery chemicals escaping into freshwater subsurface bodies. Under the course of action that is currently being followed, no data on groundwater contamination are likely to be obtained until a variety of pollutant events occur that are serious enough to require detailed study.

   The types of data that should be assembled at this time include: (a) Mass balance calculations for existing projects (and the associated data required to make those calculations) in order to provide an accounting of what quantities of chemicals have left the injected-well-reservoir-producing-well system. (b) Subsurface flow modeling to determine routes of movement, expected speed of movement, and expected range of movement. (c) A variety of monitoring data to identify downward flows from surface disposal, flows away from improperly capped wells, flows away from improperly sealed wells, and flows through structural fractures. (d) Detailed studies of the circumstances surrounding any significant pollutant events involving groundwater contamination. (e) Chemical budgets (employing the above four types of information [a-d]) accounting for quantities of chemicals used, quantities of chemicals degraded in the reservoir, quantities of chemicals produced from the well, and pollutant levels.

3. Degradation products. The range of chemicals into which the injected chemical formulation may degrade in a reservoir have not been studied.[56] Degradation is also of importance to petroleum engineers as they seek to understand the quantities of chemicals that will be required, in an enhanced recovery project, to satisfy the engineering requirements. Processes that have been identified as having a significant impact on the state of injected chemicals include thermal degradation, biological degradation, and physical degradation resulting from the breakup of long molecular chains as the molecules experience shear while being injected under pressure. Until this area is studied further, it leaves a whole dimension of enhanced recovery environmental problems undefined.

4. Information is required to characterize the fugitive emissions occurring from steam drive processes, in situ combustion processes, and chemical flooding processes. This will involve measurement of gases in gas traps, producing well vents, and atmospheric conditions in the vicinity of injection and producing wells for in situ combustion and steam drive.

5. Develop information to perform well failure risk analysis. An extensive data assembly effort will be required to characterize the engineering parameters of well construction, well casings, well completion, and old well sealing, to allow a reliable calculation of the probability of well failure events.

6. Secondary impact associated with chemical supply and chemical manufacture risks. Data bases need to be developed to provide reference information on:

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[56] Preliminary work is underway by the DOE BETC.

(1) current levels of demand for classes of enhanced recovery chemicals, (2) predicted levels of demand under various commercialization scenarios, (3) current production capacity, and (4) industry's projection of new plant capacity. In addition to this evaluation of product availability and manufacturing capacity, analysis of the pollutants generated by chemical manufacturing is required. Most of the chemical manufacturing processes required to produce the polymers, surfactants, and other chemicals used during enhanced recovery do not fall into the categories that have been studies by the EPA Effluent Guidelines Development Document Series. Process flow sheets need to be developed for these industries and characterization of the air, water, and waste residues from these industries will be needed. Total pollutant levels expected from enhanced recovery industry chemical supply can then be calculated.

PROPOSED MONITORING ACTIVITIES

Many of the required types of environmental data needed to assess enhanced recovery pollution are missing because little or no monitoring has taken place at enhanced recovery sites. It is absolutely essential that monitoring programs are set up and begun in the near future in order to collect this data and thus to understand the health and environmental impacts specific to enhanced recovery technologies.

The first step in data gathering is to specify monitoring procedures. These include: media to be sampled, specific sampling procedures for each of the media to be sampled, constituents to be sampled, sample storage procedures for each of these constituents, recommended spatial patterns for sampling of each medium, and recommended sampling frequencies for each medium. Specific pollutants and pollutant impacts that have been identified as known environmental problems and thus warrant current monitoring include:

1. Steam drive air emissions. SO_x, NO_x, particulates, H_2S, hydrocarbons, and complex organics should be monitored. In addition, the nonhydrocarbon organics should be identified. Some source monitoring is carried out by CARB and oil operators at present.

2. Fugitive emissions from steam drive and in situ combustion processes. These should be monitored at the sources when identifiable indirectly via monitoring of the ambient levels in the field for all of

the above constituents. Particulates should be analyzed for trace metal and organic constituents.

3. Noises from construction and drilling occurring within several thousand meters of populated areas. Monitoring of noise in these ares is necessary.

4. Heavy metal content of resultant brines. Samples should be analyzed for a wide range of metals to determine hazards associated with brines.

5. Organic and trace metal constituents of produced water. Monitoring should be done to determine the concentrations of these.

6. Water quantities used in enhanced oil and gas recovery projects. Parameters to be monitored include the volume of water used per unit time, quality of water used (fresh, sewage effluent, brine), volume of water produced per unit of time, quality of water produced, volume of water recycled per unit of time (if any), and volumes of produced water reinjected into the producing formation per unit of time.

7. Quantity and quality of scrubber water generated through air pollution control for steam drive. Constituents to be monitored include trace elements (metals) and organics.

8. Leaching from surface disposal of scrubber sludge, drilling cores, and unacceptable chemical mixtures, that is, not usable for flooding because of mixing or component problems. Monitoring is needed to determine the extent of this.

Criteria for Developing a Monitoring Plan

There are three main aspects of an EOR project that must be considered when a monitoring plan is being developed:

1. The geological and hydrological subsurface characteristics of the site on which the plan will be implemented.

2. The exact purpose or desired output of the monitoring program.

3. The available budget for actual operation of the monitoring plan.

The final monitoring plan set up for any project represents a balance between demands made by site characteristics, purpose, and budget considerations.

Reservoir Fluids Composition Monitoring Plan

A monitoring plan for determining reservoir fluids composition is necessarily site specific because the methodology for any groundwater sampling program depends on the nature of the groundwater system, the direction and rate of the ground water flow, the availability and accessibility of groundwater testing sites, and the length of time over which records on groundwater quality have been kept.

A general outline for a monitoring plan at a specific site follows:

I. Assemble data on the locations and depths of all registered water wells and oil wells in the area from state geologic surveys and state water surveys. Compile a list of all possible groundwater testing sites (water wells, observation wells, old oil wells). A network of testing sites within the field at different depths and locations is required.

II. Collect information on all previously logged wells in the area. From these data identify saline and fresh water aquifers, impermeable strata and local geological formations. Combine this information with State Survey information to produce a record of all problems, near surface and at depth, resulting from contamination predating enhanced recovery activites.

III. Determine groundwater gradient or direction of flow for the local subsurface system. This is done by tallying the pressure of the different water wells at different depths and locations and interpreting this in terms of subsurface fluid flow directions and gradients. The greater the determined flow, the greater the frequency of sampling required.

IV. Summarize existing data and estimate the nature of the groundwater system, that is, how fast contaminants would be transported from one point to the next in the network of testing sites. This information is essential for the interpretation of test results, particularly concentration gradients.

Va. Set up groundwater sampling stations. Refer to a number of existing monitoring guidelines, for example Beck et al. (1976).

Vb. Sample and test background levels of water quality, that is, test groundwater presumed to be unexposed to the possible EOR contaminants.

VIa. For a cost-effective program a surrogate parameter is chosen that will be representative of the suite of chemicals injected. The detectable threshold value of the surrogate parameter then serves as an initial screen.

VIb. Test injection fluid or some commonly used dilution of the EOR chemical being used to assume that the surrogate parameter will detect its occurrence in ground water appropriately.

VIc. Obtain available data from manufacturers regarding toxicity values and typical concentrations of the chemical that may occur in the subsurface regime to determine a relevant threshold value for a surrogate parameter.

VId. Develop a quality control plan for the use of the surrogate parameter, which would include periodic checks and calibration of the threshold level to insure that it would signal the occurrence of significant concentrations of EOR/EGR chemicals.

PROPOSED HIGHEST PRIORITY RESEARCH

Of the information needs noted previously some can be addressed by research efforts. The following are the efforts most likely to increase the understanding of enhanced recovery pollutants:

- Air emissions control options. Further study of the whole issue of air emissions associated with steam generation is required (pending the outcome of the currently ongoing DOE study on this topic being performed by Radian Corporation). Getty recently temporarily abandoned much of its Kern County steam activities because of SO_x and NO_x control problems.
- Produced water recycling. Improved systems would allow the recycling of produced waters as enhanced recovery injection fluids.
- Nonstructural controls. Options for field management practices and recovery technology methods should be developed as an alternative to technology-based control devices.

- Hazardous residues disposal. Methods for the degradation of hazardous wastes for ultimate disposal require development.

- Perform cost/benefit analyses. These include environmental externalities to determine reasonable levels of control for each EOR and EGR process and to determine the tradeoffs that exist at various levels of control.

- Toxicity Studies.[57] These should include:

  - Bacterial screen for mutagens/carcinogens
  - Mammal carcinogenic bioassays
  - Aquatic toxicity bioassays
  - Agricultural plant bioassays

- Study the fates of EOR chemicals in the reservoir and the aquifer. There are two alternative approaches. One is to survey the available data regarding transport and degradation of chemicals used in EOR/EGR. This approach is hampered by the confidential nature of the results obtained in laboratory research by chemical firms and by oil companies engaged in private EOR/EGR projects. Some DOE work is under way in this area. The second approach is to develop independent EPA data for a selected list of chemicals of concern.

- Resource availability for enhanced recovery. Chemical production capacity should be surveyed and an analysis of current and projected demands should be made.

- Apply subsurface flow/aquifer models to allow study of migration of EOR chemicals from leaks in old well casings and the like. A data requirements list for calibration and verification of the model should also be developed.

- Develop monitoring data. These data are to identify the extent of groundwater pollution. Almost all environmental studies to date have relied on conjecture, laboratory results, or models. Monitoring programs which result in no positive signs of contamination would provide useful information; however, monitoring will be most useful in response to suspected contamination events. Prior to such events, baseline data will be a useful benchmark.

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[57] Preliminary studies by the DOE are now under way (Silvestro, 1980)

- Develop a monitoring protocol for EPA monitoring of EOR/EGR activities. The DOE Booz/Allen results should be adapted to the institutional needs of the EPA.

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